DAQ Hardware

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A Hands-on Approach

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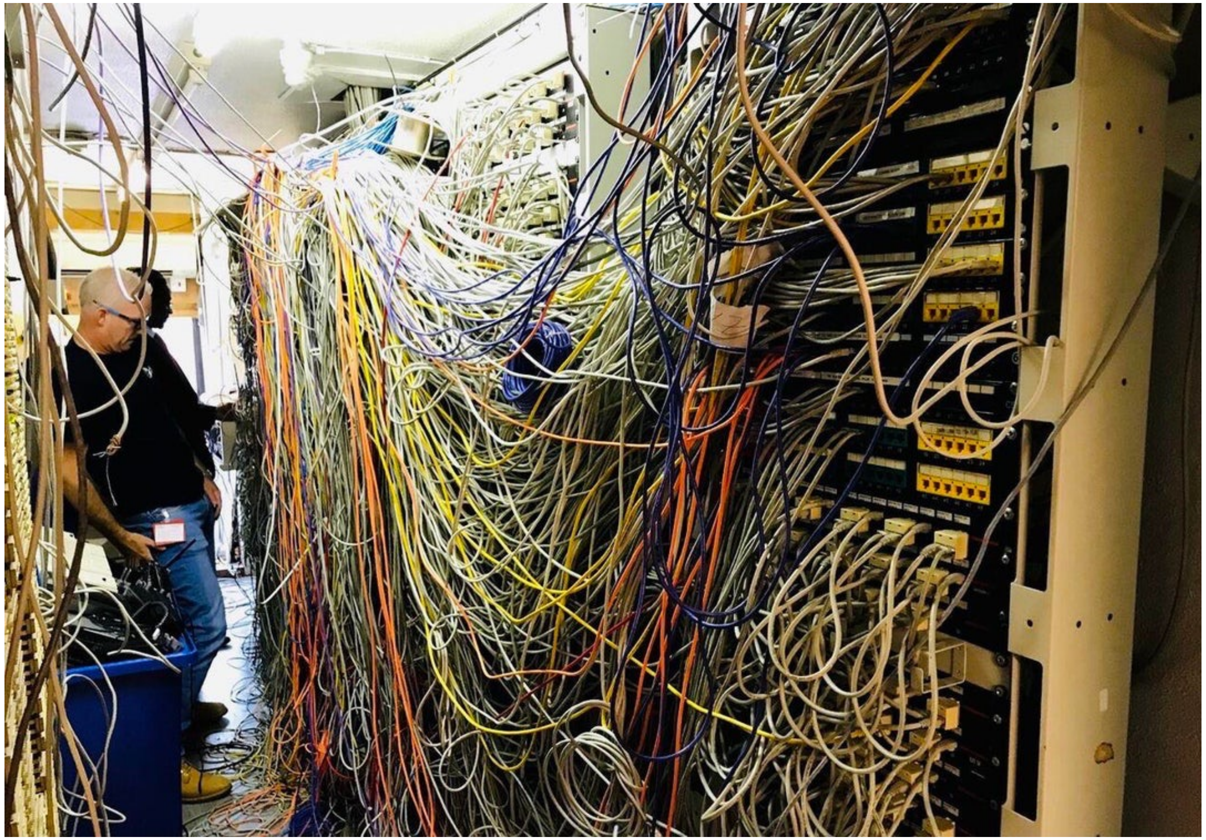

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Introduction

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  - We will discuss quite simple different experiments, requiring different techniques and components
  - We also have some good real data to discuss
  - We'll see also issues you can encounter

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How does HW work?

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How does HW

Where do physics data come from?

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…does HW…

Where d…

How do physics events become bits and numbers?

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- Acknowledgements
  - © Andrea Negri (Univ. of Pavia, Italy)
  - © Wainer Vandelli (CERN/PH-ATD)
  - © Sergio Ballestrero (Univ. Johannesburg & CERN)
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Introduction on DAQ

From previous lecture (A. Negri)

➔"Data Acquisition" on Wikipedia: data acquisition (DAQ) is the process of **sampling signals** that measure real world physical conditions and **converting** the resulting samples into digital numeric values that....

➔Data acquisition is an **alchemy** of electronics, computer science, networking, physics

- …. resources and manpower matter as well, …

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➔DAQ is a wide and vast field, sometimes depending on the context

➔I will mostly refer to DAQ in High-Energy Physics experiments

➔We'll discuss only the basic principles of DAQ

➔Some of these might be the starting points for your next experiments

Electronics: What is needed for?

Typically, electronics interfaces DAQ with the detector

➔Collect electrical signals from the detector. Usually a short current pulse

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Main roles:

1: Acquire & Shape the signal to optimize different, **incompatible**, characteristics → Compromise

- Detect minimum detectable signal
- Precise energy measurement
- Fast signal rate
- Precise timing
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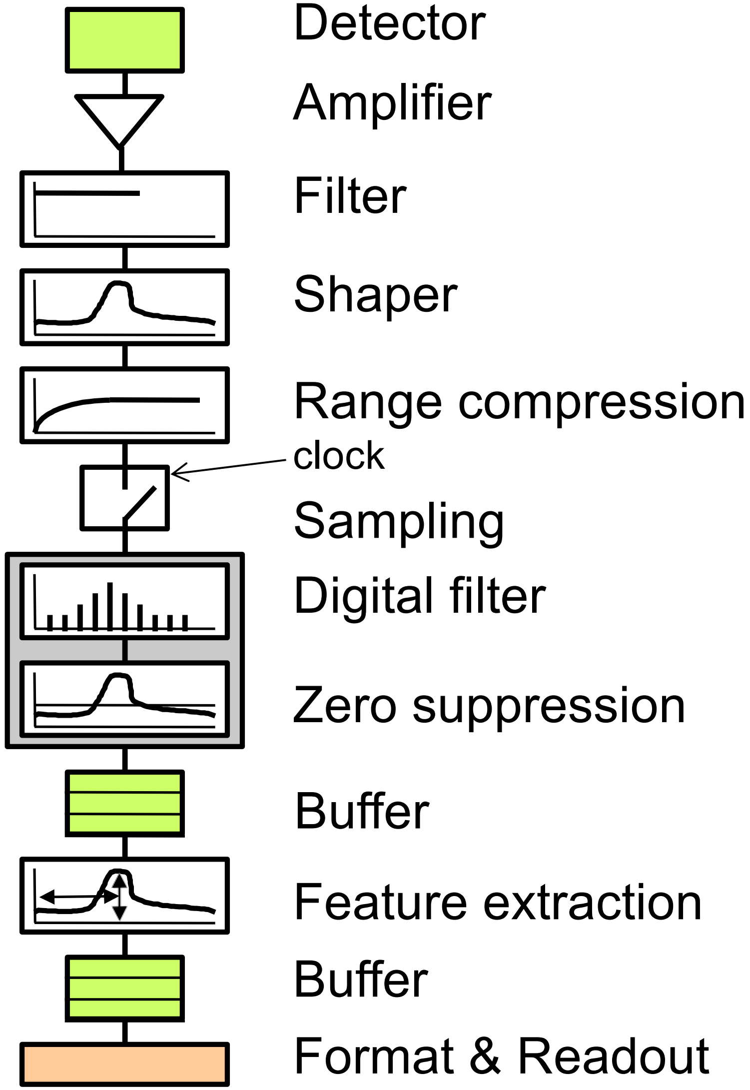
2: Digitize the signal

- provide a digital representation of the measurement
- allow for subsequent processing, transmission, storage using digital electronics → Computers, Fibres, Networks, …

Readout chain



➔Front-end electronics very specialized

- translates signals from a specific detector to a standard digital world
- custom build to match detector characteristics

➔We cannot discuss all design and architecture details

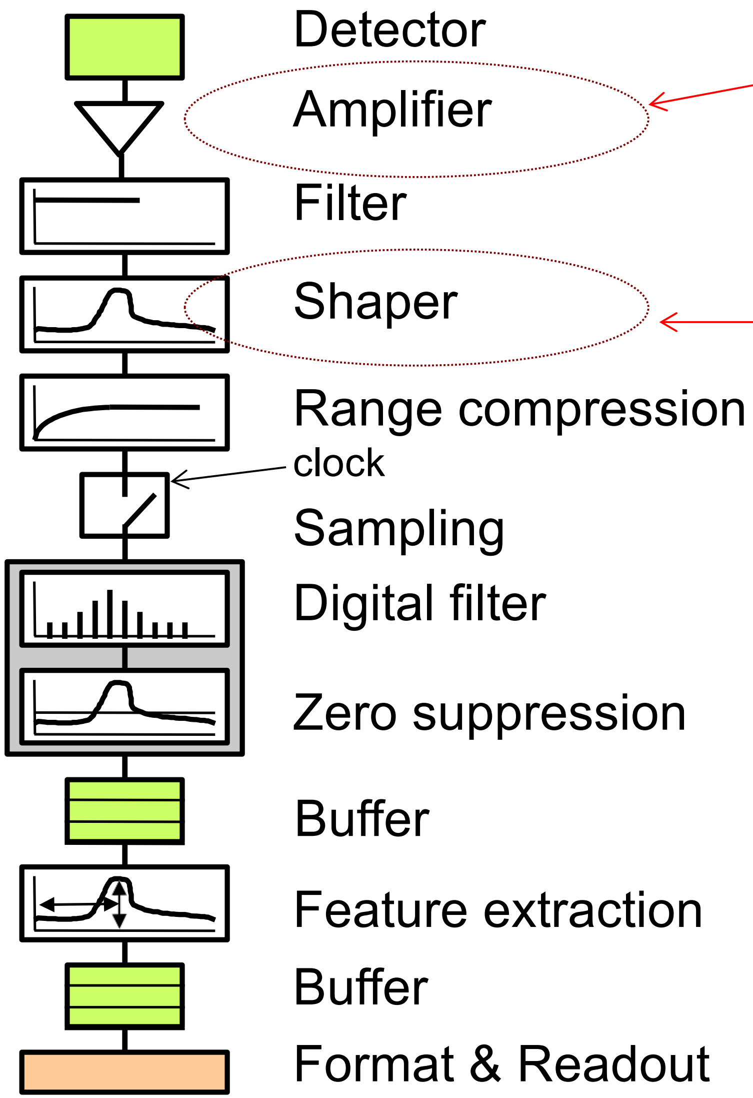
- if you are into electronic design you already know many topics

➔I want to provide you with basic guidelines

- This hopefully may help you when dealing or choosing commercial electronics
- If you need to design custom electronics, you need expertise in that field

➔We only discuss selected functions and principles

Readout chain

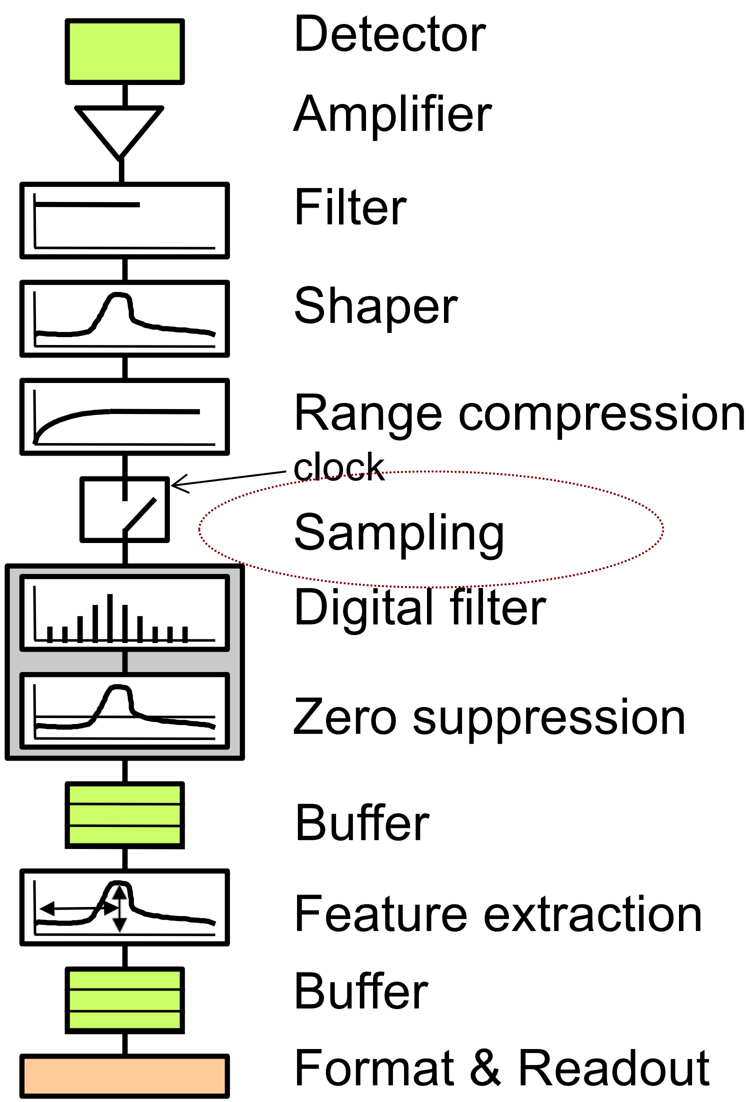


Main functionalities:

- Amplify the tiny signal produced by the detector
- Improve Signal-to-Noise ratio

- Receive the (amplified) signal and give it a specific shape

Readout chain

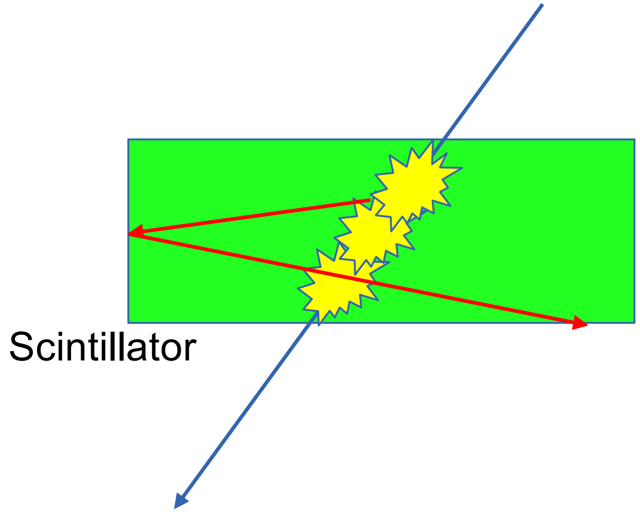


Outline

- Introduction
  - DAQ, Electronics & Readout Chain
- Measure energy deposition
  - Scintillator setup
  - Photomultiplier
  - Analog-to-Digital conversion
  - Charge-to-Digital conversion
  - QDC in real life
- Measure position
  - Wire chamber setup
  - Time-to-Digital conversion
  - TDC in real life
- Corollary

You'll see in Labs 2-3

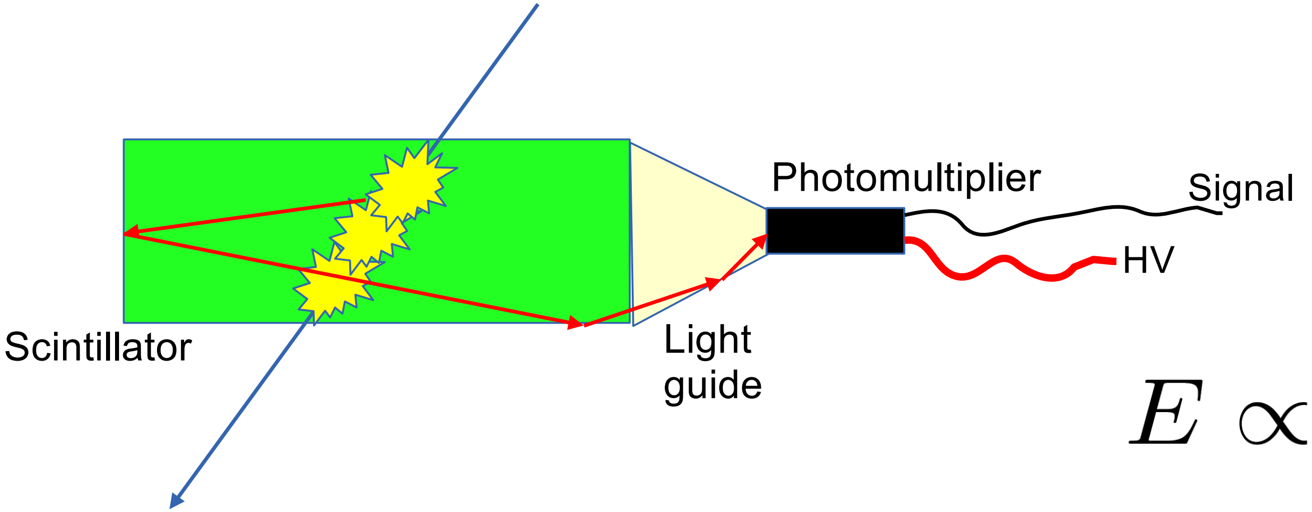
Energy measurement



$$E \propto N_\gamma$$

- Measure energy deposited by a particle traversing a medium
- The medium (detector) is a **scintillator**
  - Molecules, excited by the passing particle, relax emitting light
  - The amount of light is proportional to the deposited energy
  - We want to collect light with the highest possible collection efficiency

Energy measurement



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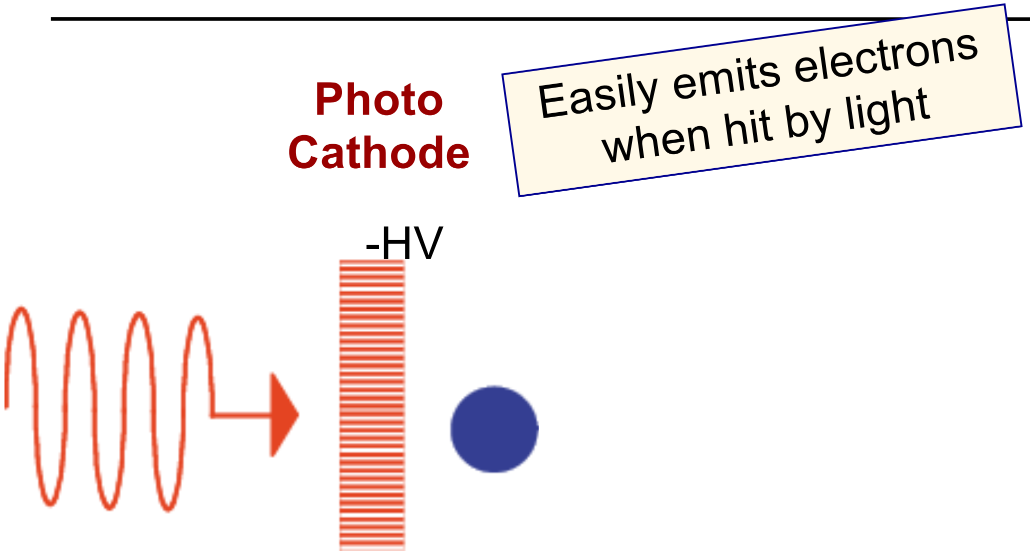
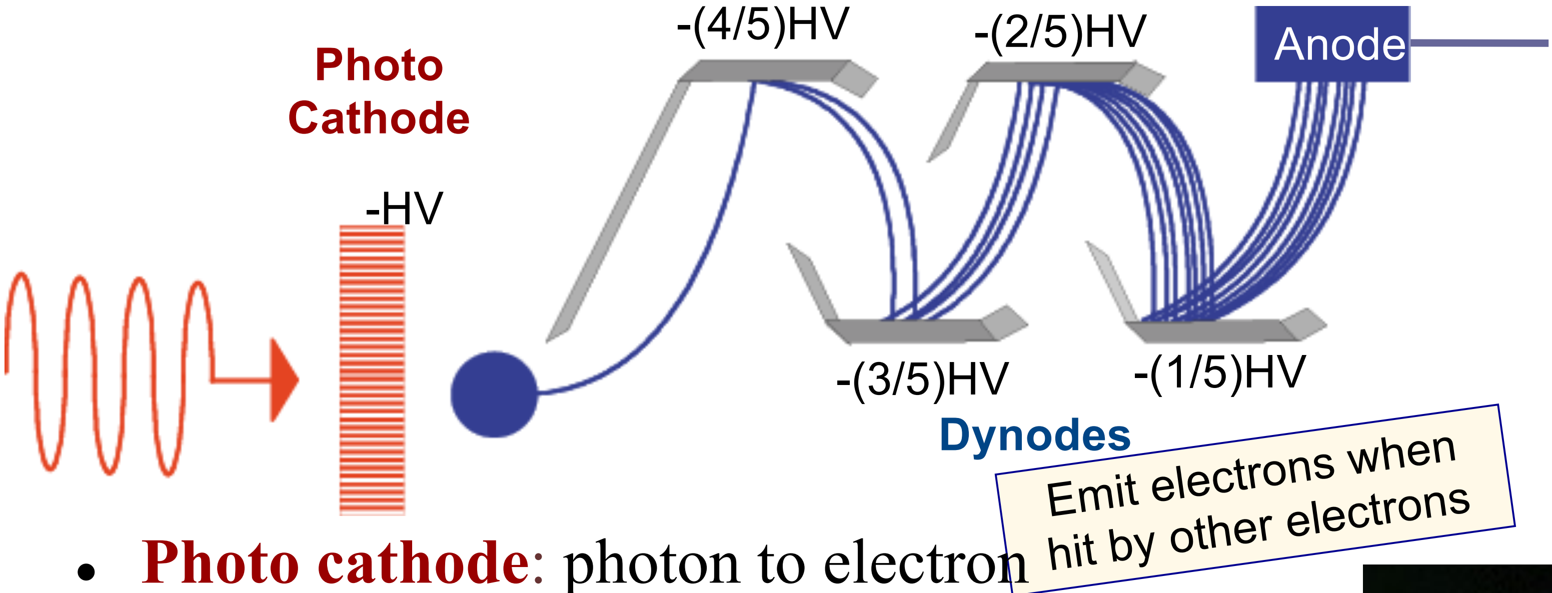
  - Molecules, excited by the passing particle, relax emitting light
  - The amount of light is <u>proportional</u> to the deposited energy
  - We want to collect light with the highest possible collection efficiency
- The light is then
  - collected, using dedicated passive optical means (**light guide**)
  - fed into a photo-detector: **photomultiplier**

Photomultiplier



- **Photo cathode**: photon to electron conversion via photo-electric effect
  - typical quantum efficiency ≈1-10% (max 30%), depends on material and wavelength

Photomultiplier



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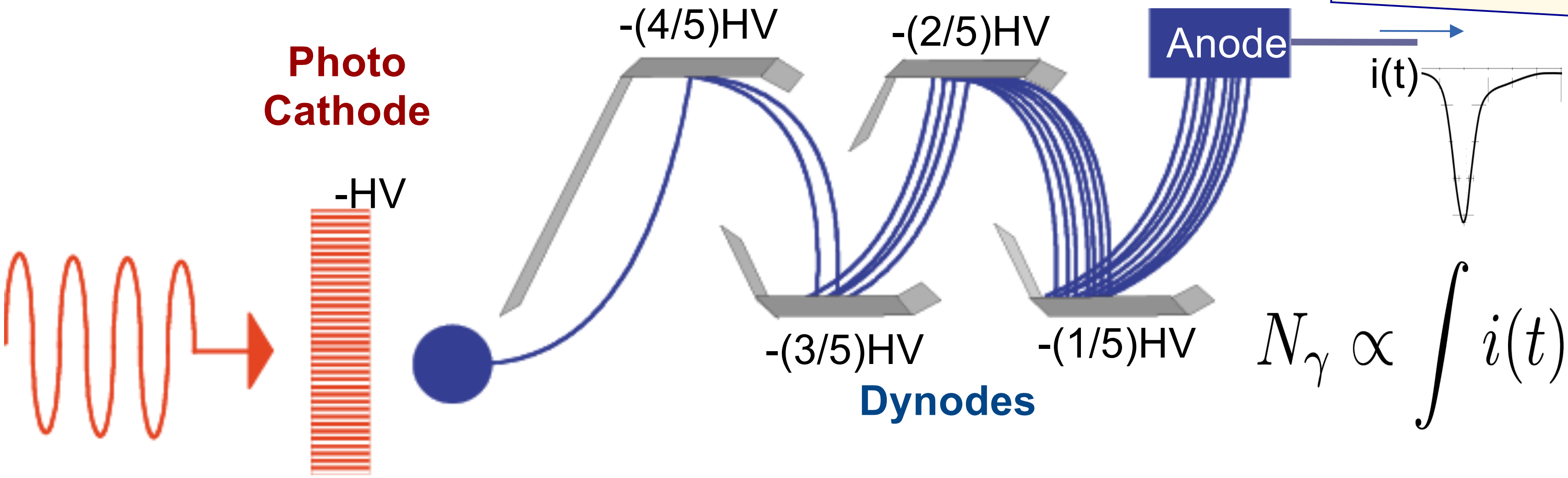
Photomultiplier

Very few photons converted into an electrical signal



$$N_\gamma \propto \int i(t)\, dt = Q$$

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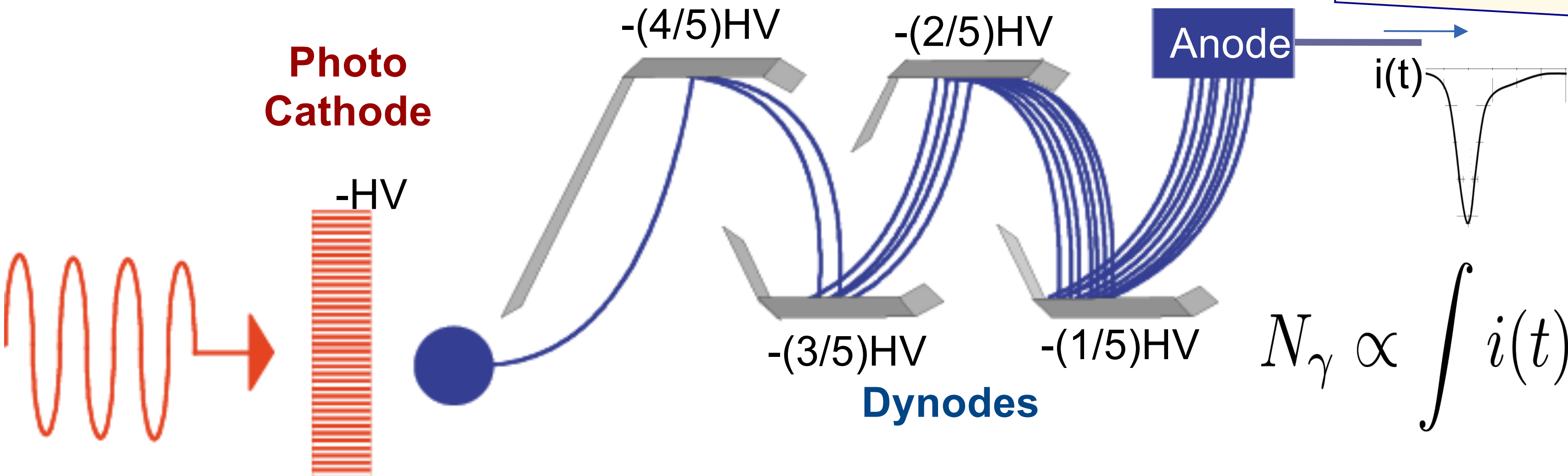

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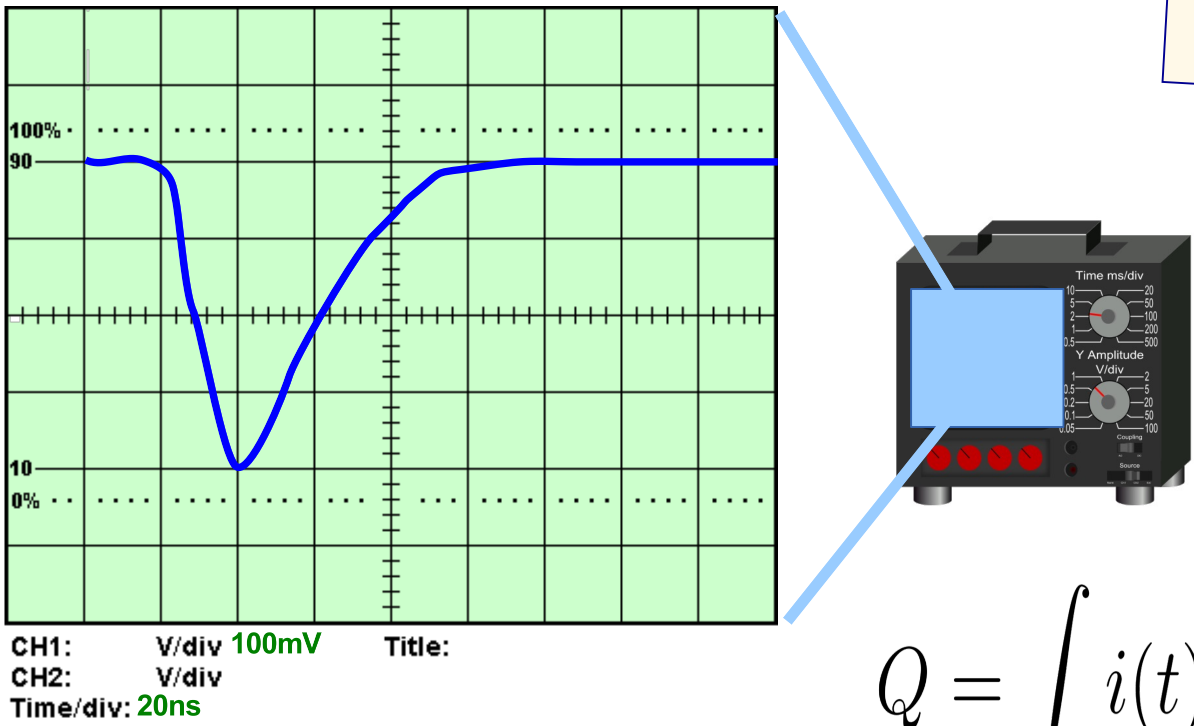
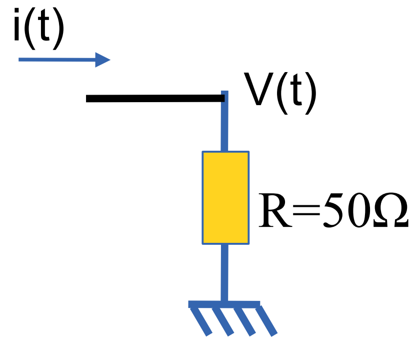
- **Dark current**: noise
  - current flowing in PMT without light, due to thermal fluctuations

Start the measurement

- Approximate Q measurement using oscilloscope
  - Linear approximation of a exponential decay

We start from an electron pulse, i.e. a current signal





$$Q = \int i(t)\,dt = \frac{1}{R}\int V(t)\,dt$$

Remeber: the TOTAL charge is proportional to the light

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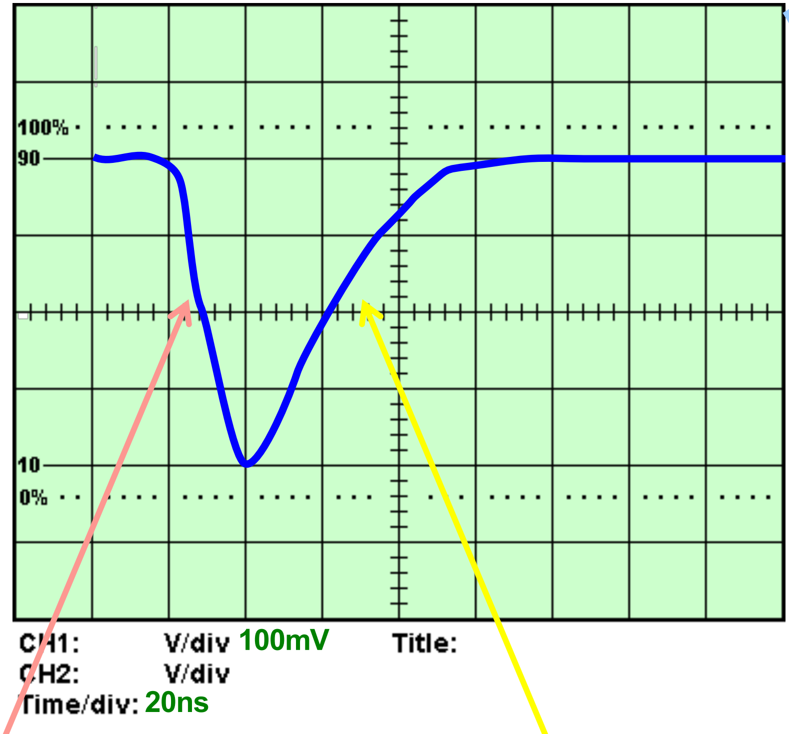
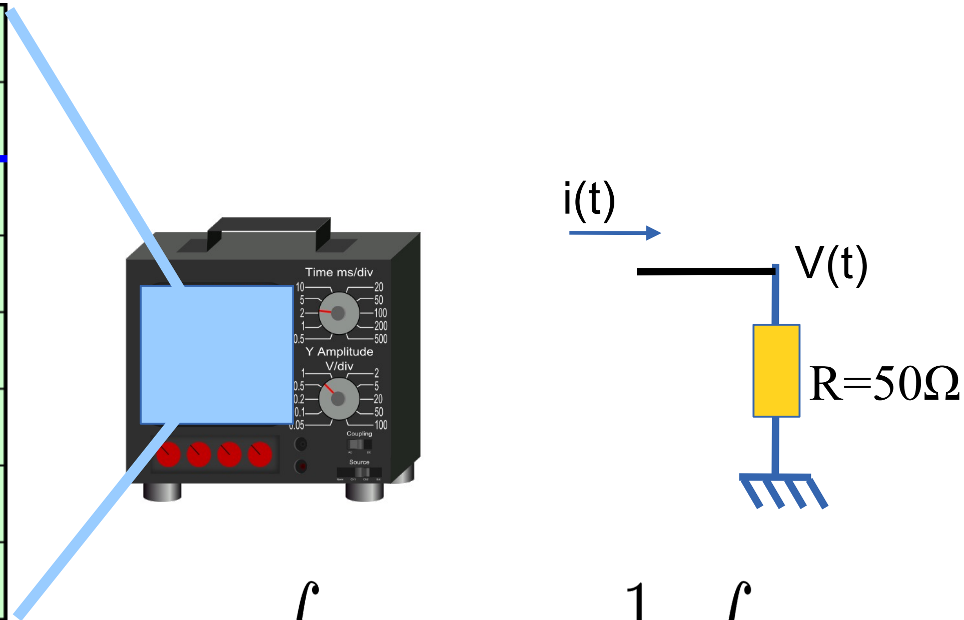


Fast rising edge

Exponential tail



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Good old oscilloscope

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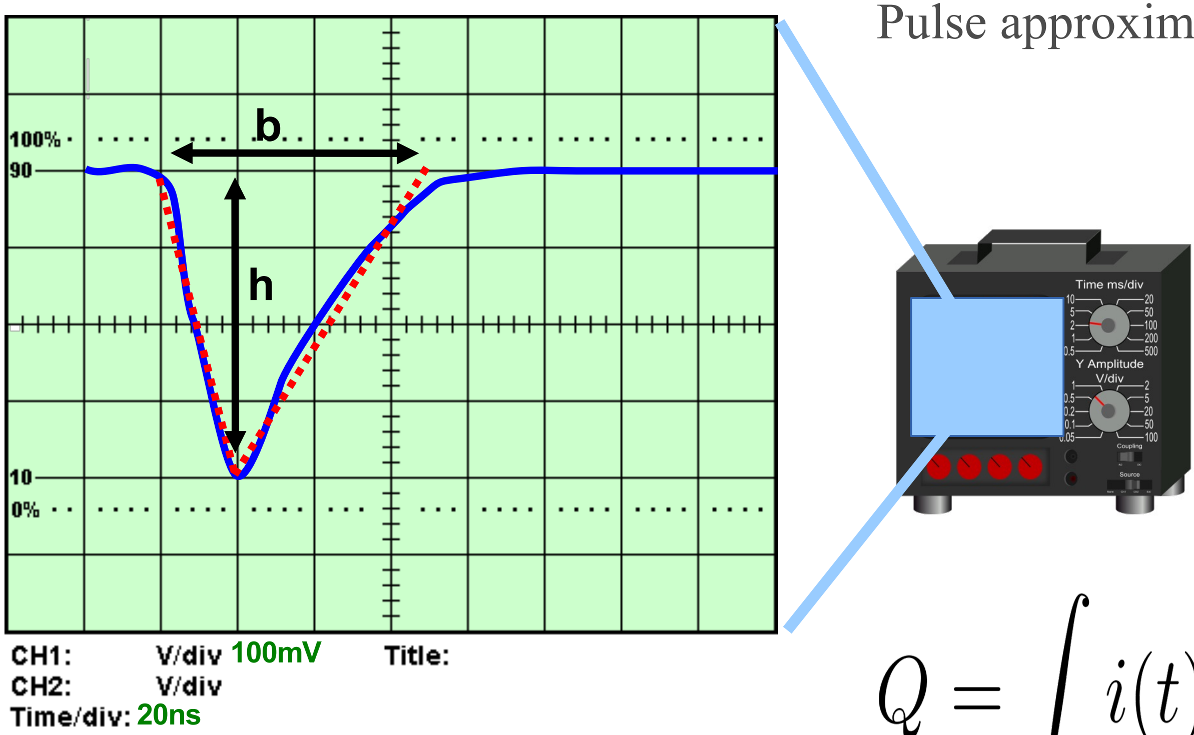
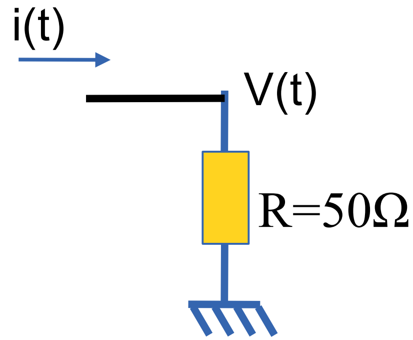
Pulse approximates a triangle





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$$Q \approx \frac{1}{R}\frac{bh}{2} = \frac{1}{50\Omega}\frac{(3.5\cdot(20\text{ns}))(4\cdot(100\text{mV}))}{2} = 280\text{pC}$$

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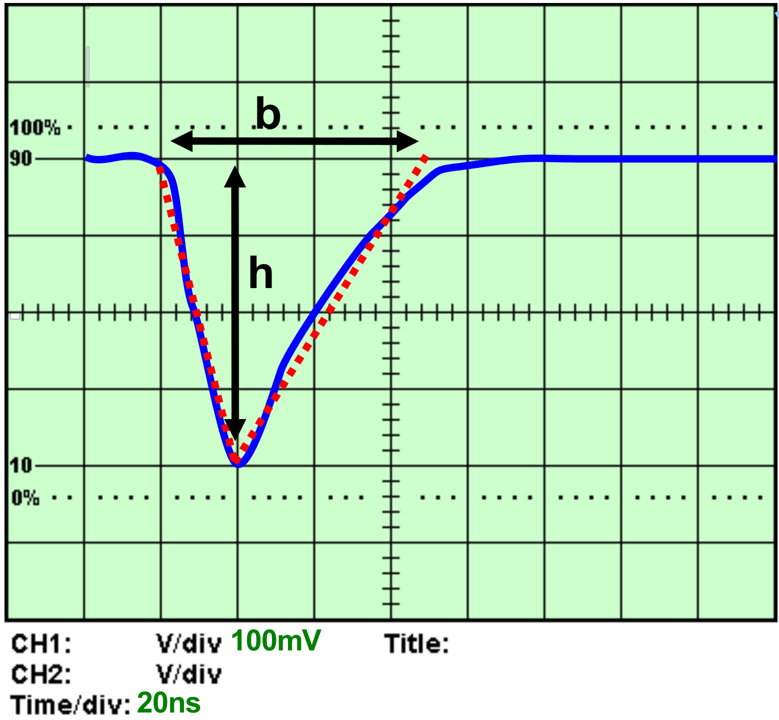

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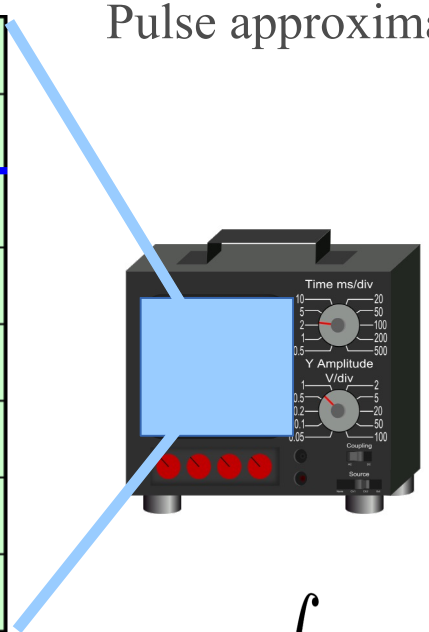

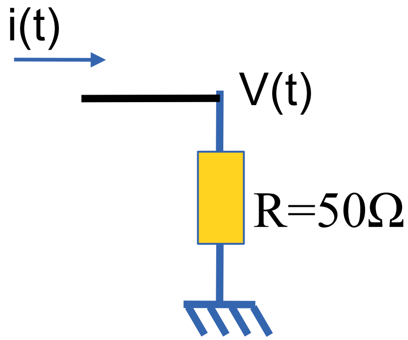

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  - Deadtime 3 – 5 min, ~ 3×10^{-3} Hz (if you are good)
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  - Save data in some digital format, fill a histogram on-line, etc ...

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LHC experiments have millions of channels to be acquired @40 MHz

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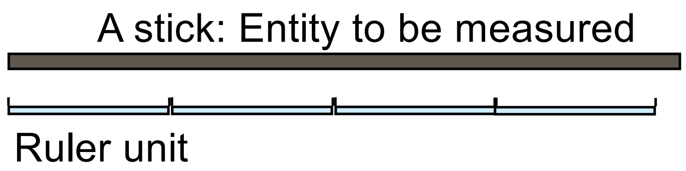
- N.B.: the oscilloscope method is still fundamental
  - it allows for the **validation** of your DAQ
  - yes, you should never thrust it a priori!

Analog to Digital Conversion

- Digitization — Lab 8
  - Encoding an analog value into a binary representation
  - By comparing entity with a ruler



We use this technique every day in our life

- Flash ADC simplest and fastest implementation
  - M comparisons in parallel
  - Input voltage V_{in} compared with M fractions of a reference voltage
    - $(1/2)\ V_{ref}/M \rightarrow (M-1/2)\ V_{ref}/M$
    - E.g.: M=3
  - Result is encoded into a compact binary form of N bits
    - $N=\log_2(M+1)$

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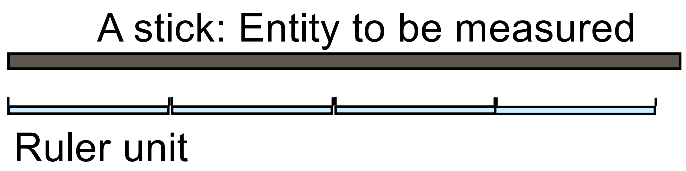

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Now our entity is a voltage, and we need one (or more) voltage as a reference

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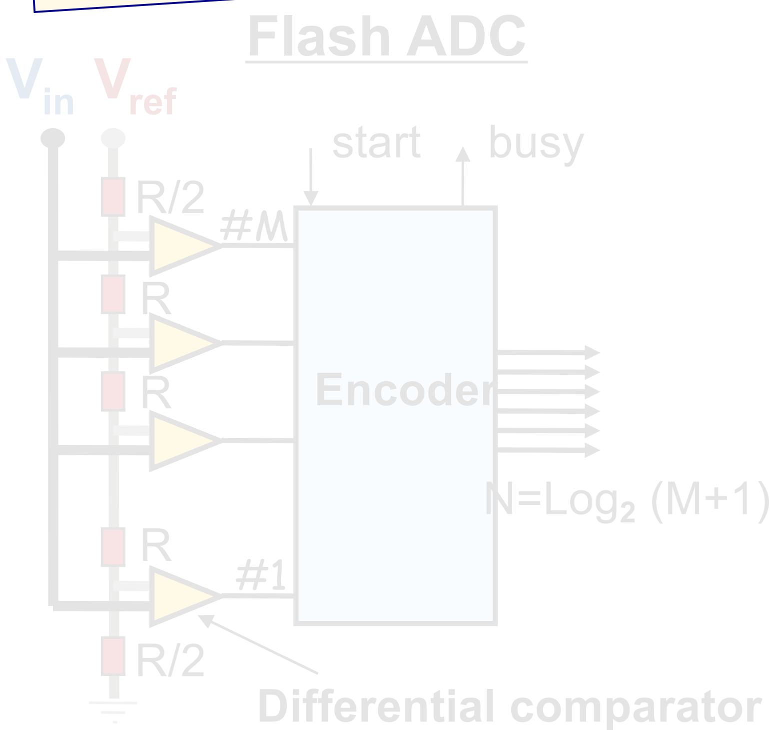

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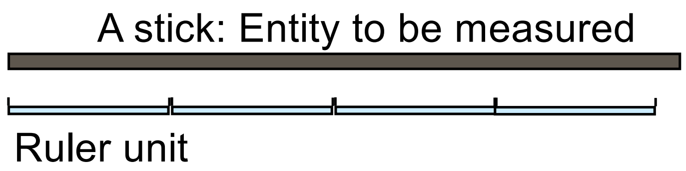

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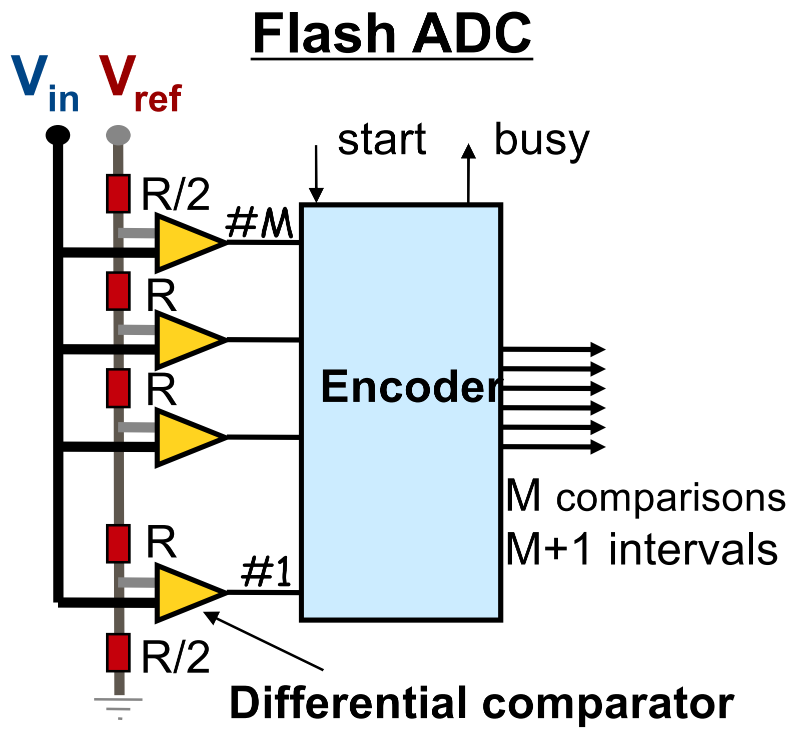

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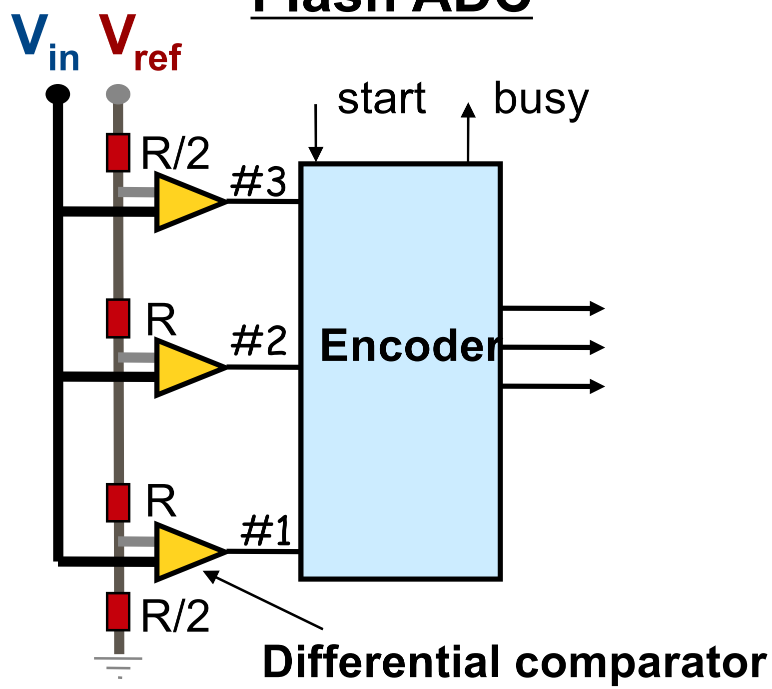
$x = V_{in}/V_{ref}$	Comparison results	Encoded form
$x < 1/6$	000	00
$1/6 \leq x < 3/6$	001	01
$3/6 \leq x < 5/6$	011	10
$5/6 \leq x$	111	11

Flash ADC



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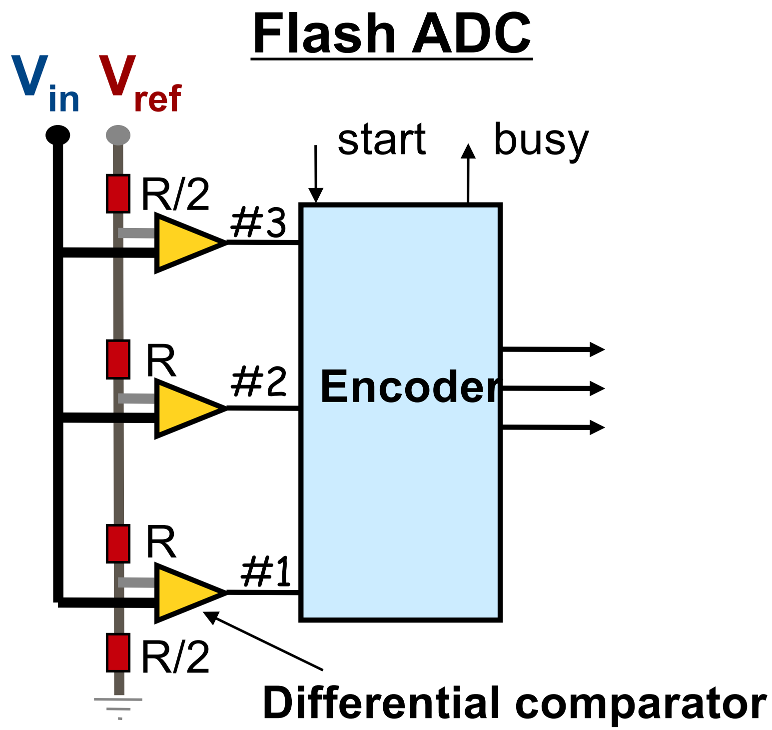

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N-bit ADC: Result is encoded in compact binary form of N bits, $N=\mathrm{Log}_2\,(M+1)$ bits

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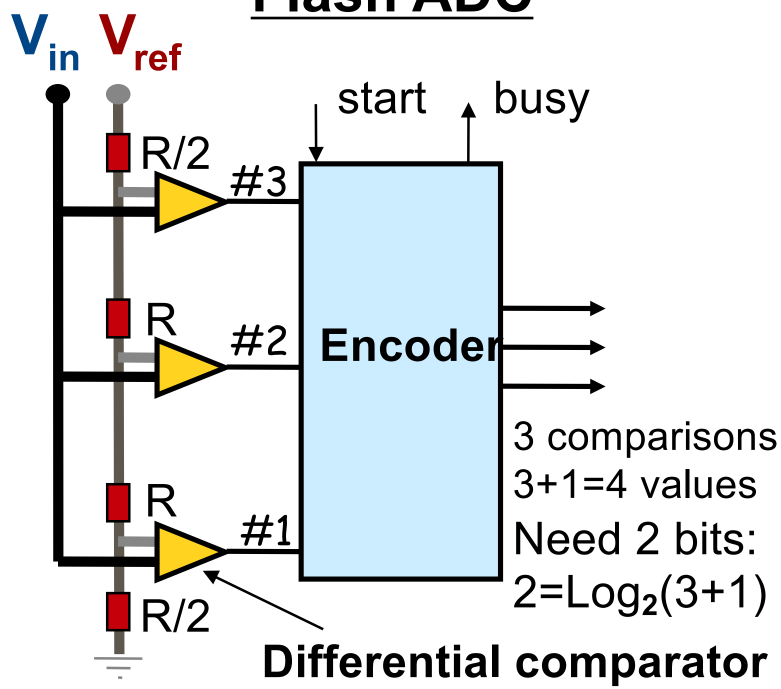
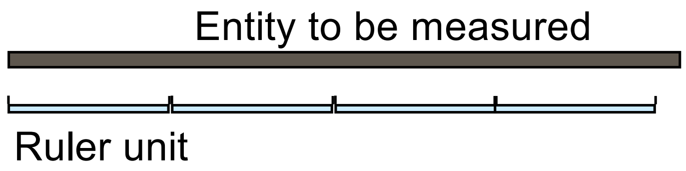
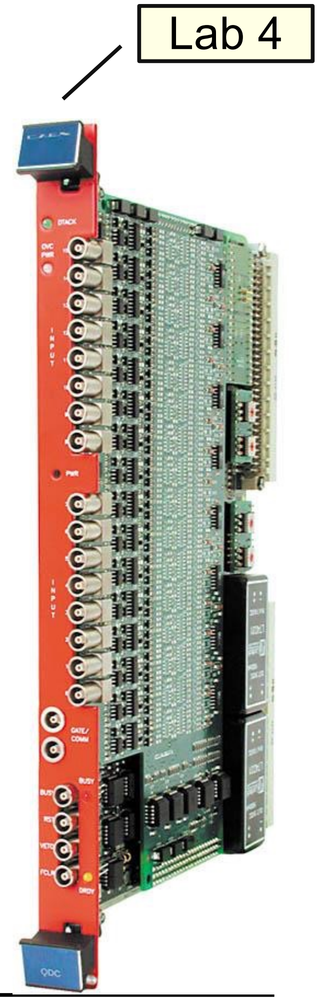


ADC Characteristics



- We want to buy the ADC that best fits with our needs:

- Ideally, we want a very fast device, with very low power consumption, with less than 1 mV resolution, etc..



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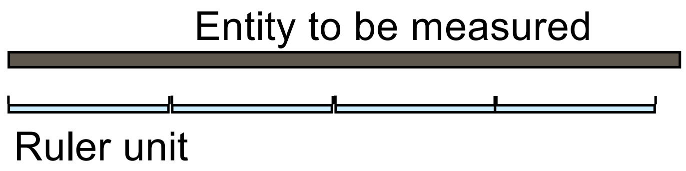

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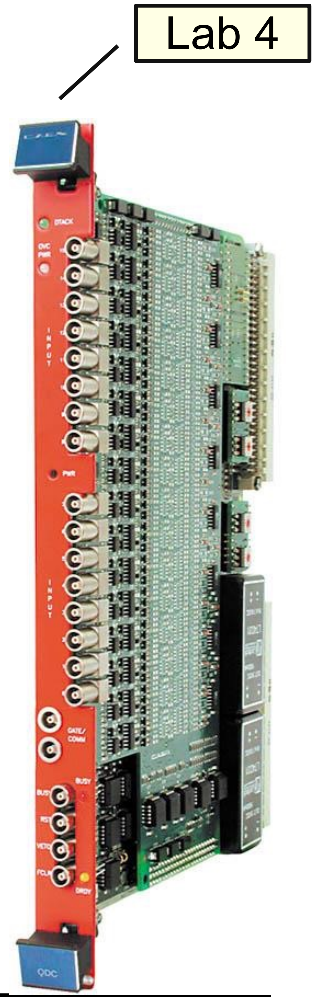
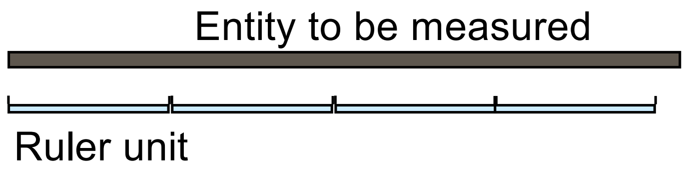
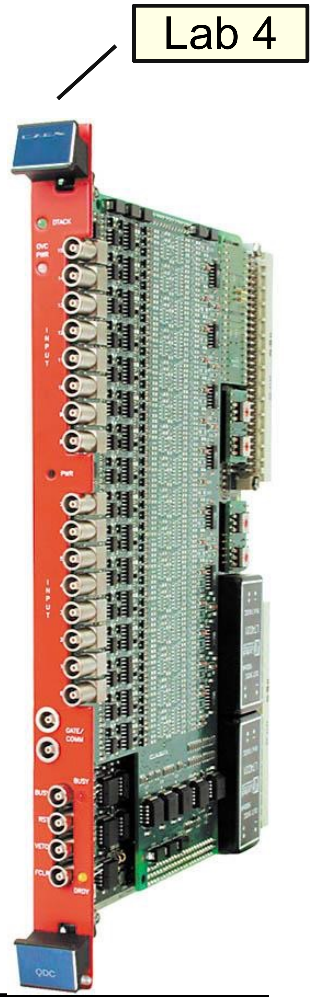


ADC Characteristics

- Resolution (LSB), the ruler unit: $V_{max}/2^N$
  - e.g.: 1V and 8bit (M=256) → LSB = 3.9 mV
  - e.g.: 1V and 10bit (M=1024) → LSB = 0.97 mV





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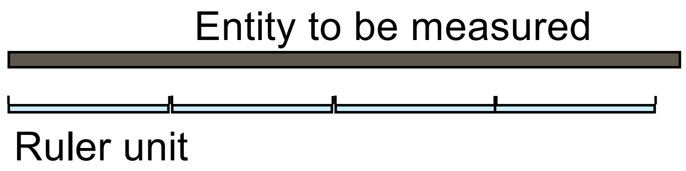
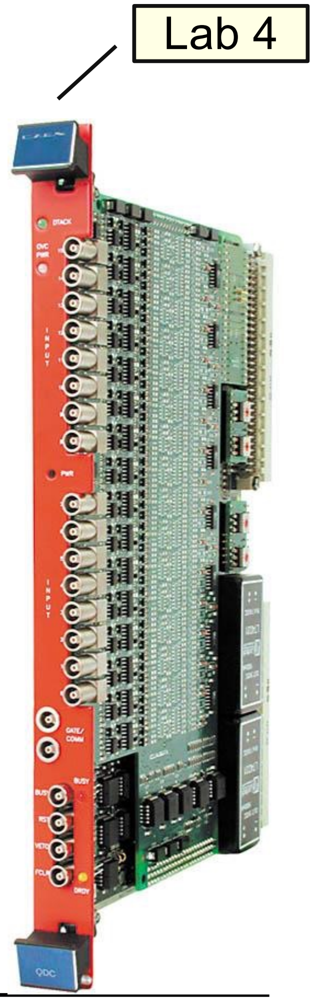


- Quantization error: ±LSB/2

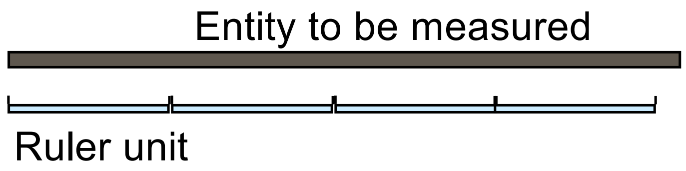
Resolution depends on the number of comparators in the ADC

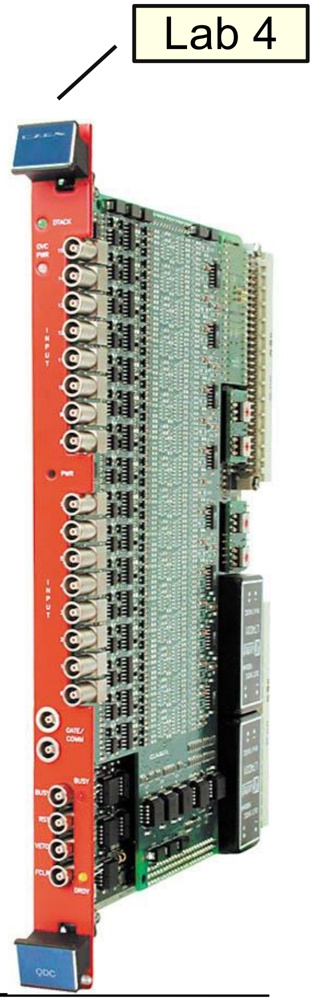


The N (number of bits) essentially tells you how many steps you have in the ADC

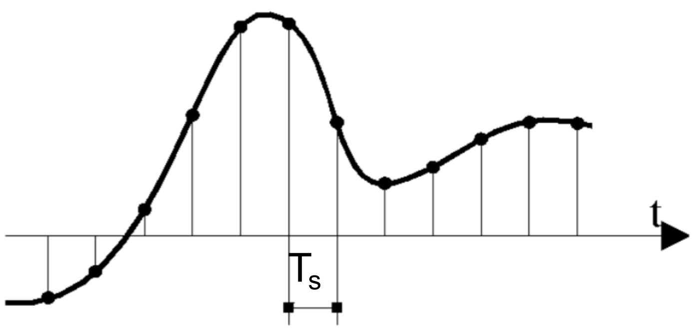
ADC Characteristics

- Resolution (LSB), the ruler unit: $V_{max}/2^N$
  - e.g.: 1V and 8bit (M=256) → LSB = 3.9 mV
  - e.g.: 1V and 10bit (M=1024) → LSB = 0.97 mV
- Quantization error: ±LSB/2

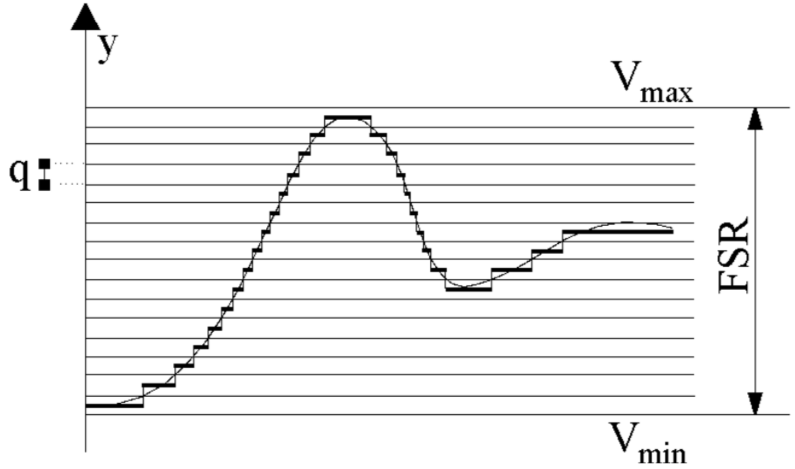




Sampled signal, S(t)



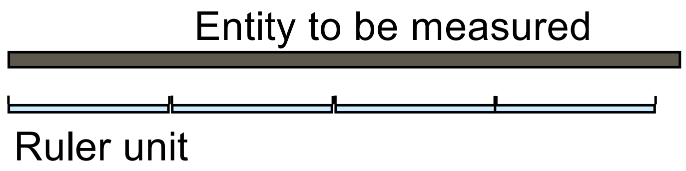
Sampling frequency, $f_s=1/T_s$

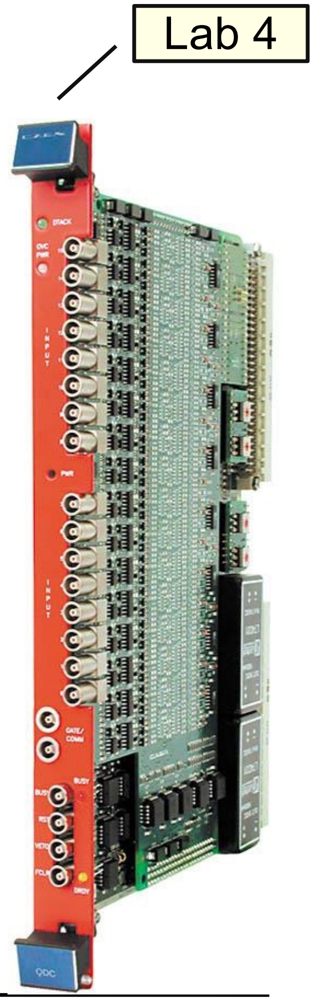


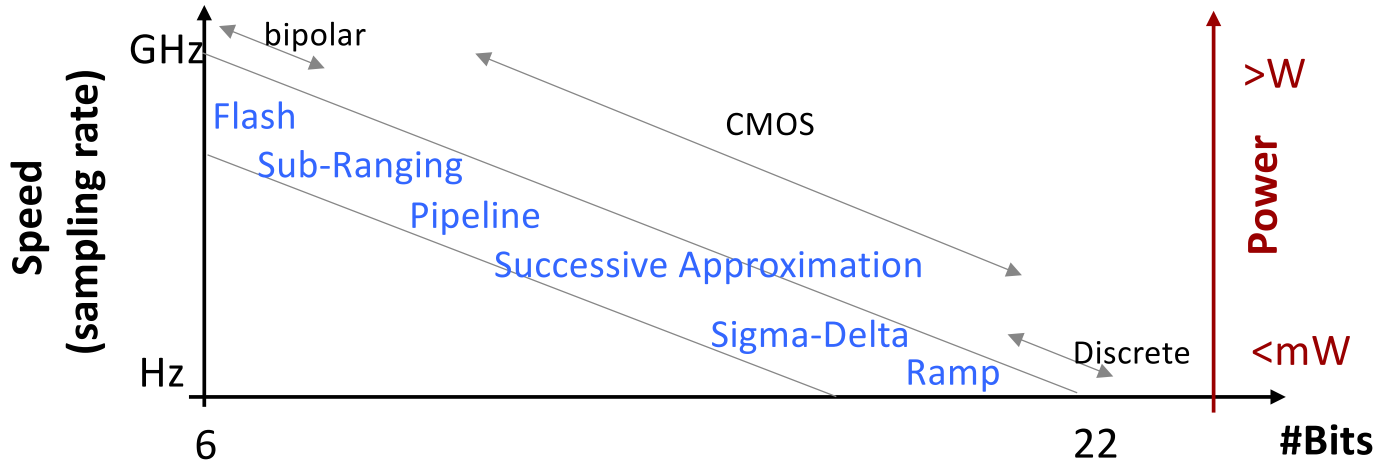
Amplitude coding with N=4
(16 different steps)

ADC Characteristics

- Resolution (LSB), the ruler unit: $V_{max}/2^N$
  - e.g.: 1V and 8bit (M=256) → LSB = 3.9 mV
  - e.g.: 1V and 10bit (M=1024) → LSB = 0.97 mV
- Quantization error: ±LSB/2
- Accuracy: see next slide
- Many different ADC architecture/technique exists
  - mostly because of the trade-off between speed and resolution







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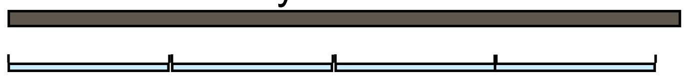
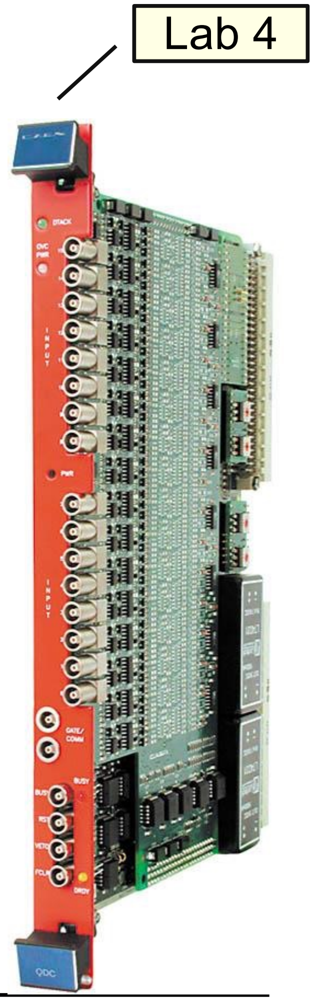
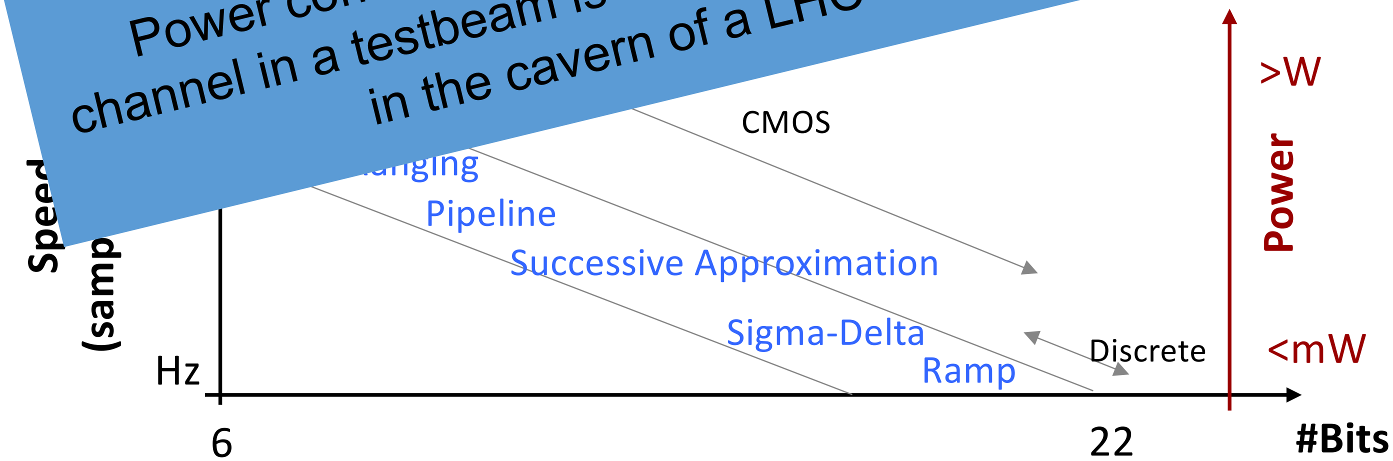
- Quantization error: ±LSB/2
- Accuracy: see next slide
- Many different ADC
  - most ... olution



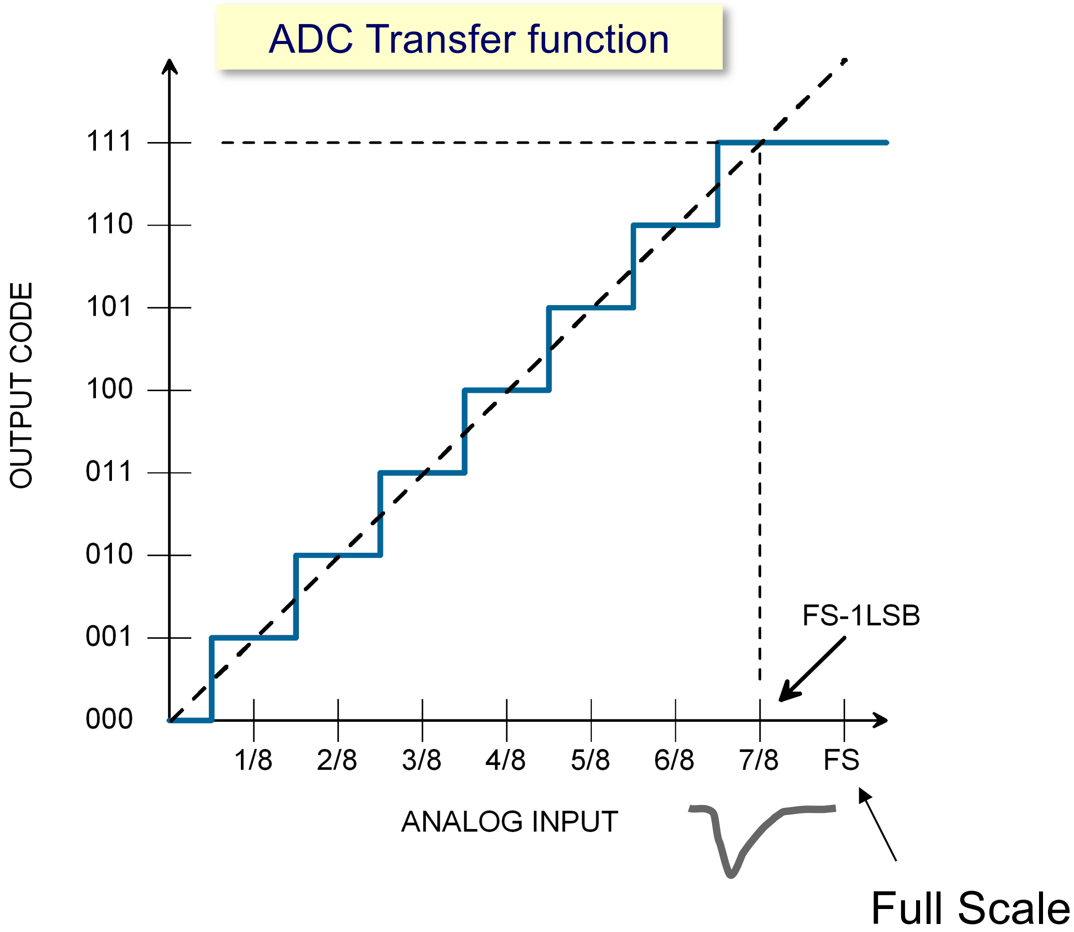


Power consumption also matters sometimes: 1 W per channel in a testbeam is very different from 1 W per channel in the cavern of a LHC experiment



ADC Accuracies

- ADC transfer function
  - Output code vs analog input



ADC (In)Accuracies

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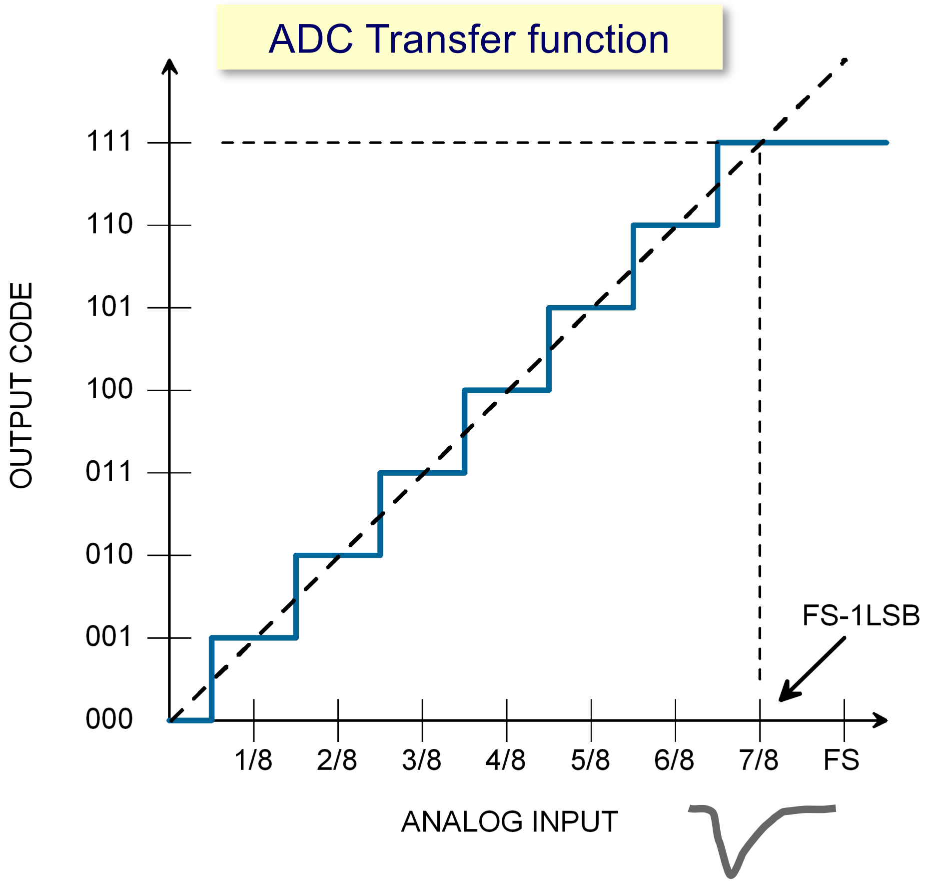
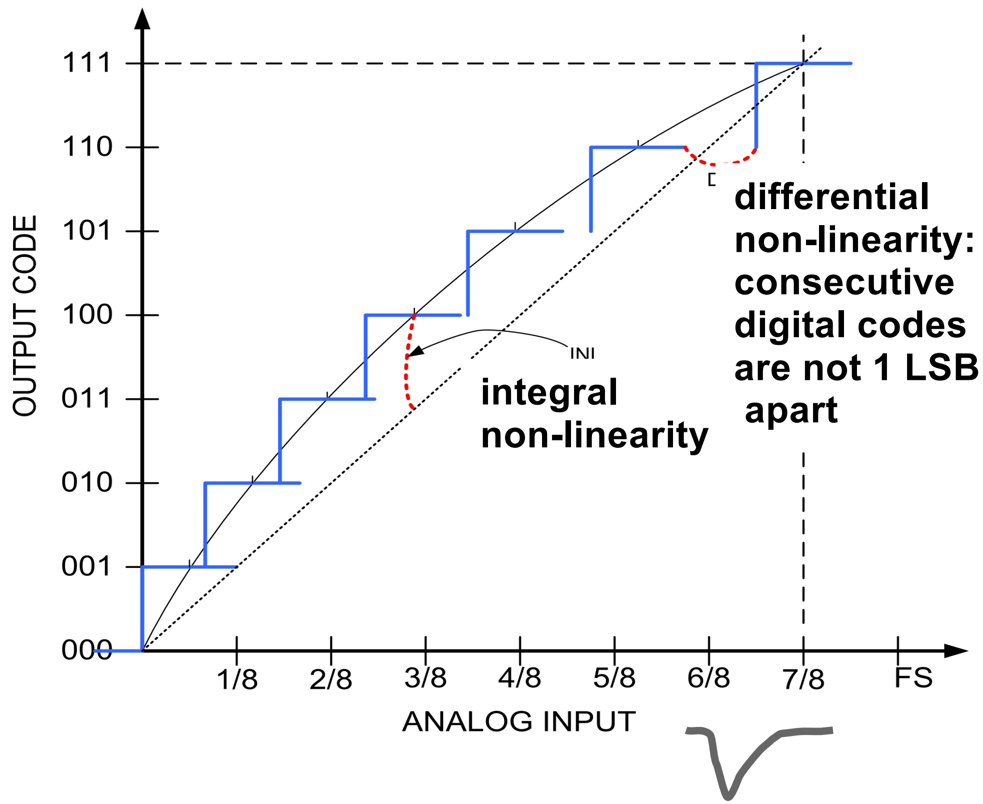
  - Output code vs analog input





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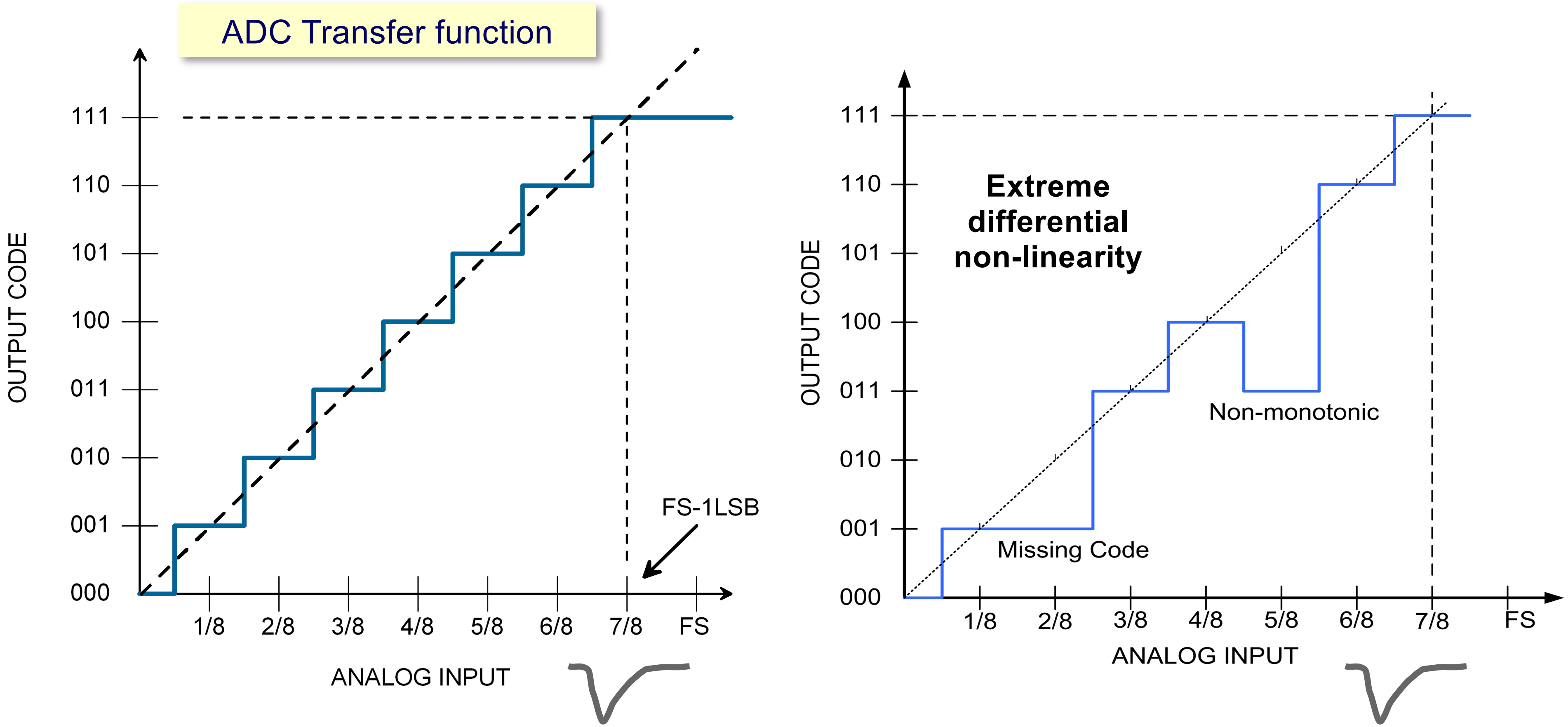
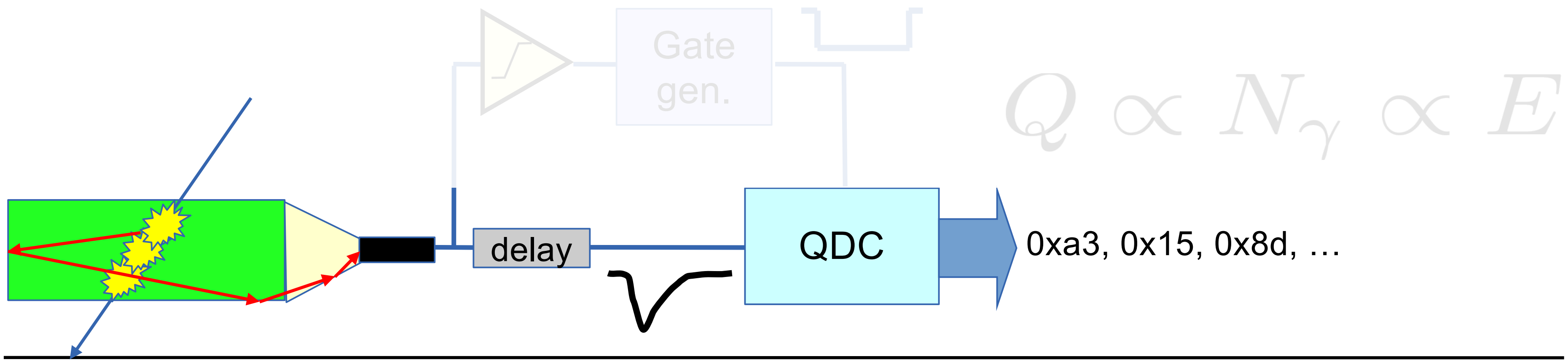


Charge to Digital

- ADC converts a voltage into a digital representation
  - However, in our experiment, we have a current and we are interested in the total charge
- We need a QDC (Charge to Digital Converter)
  - Essentially an integration step followed by an ADC
  - Integration requires limits → gate

$$I = \int_a^b f(x)\,dx$$



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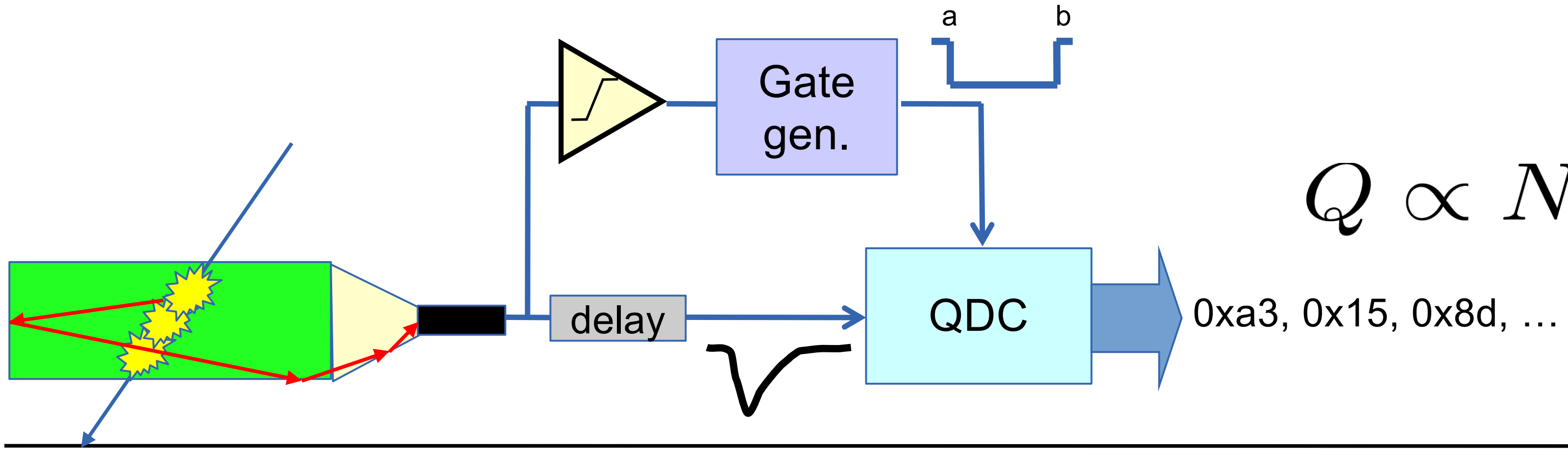


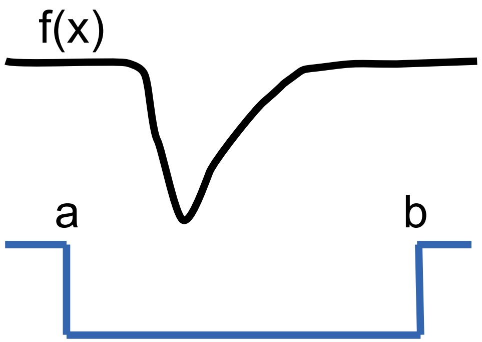
$$Q \propto N_\gamma \propto E$$

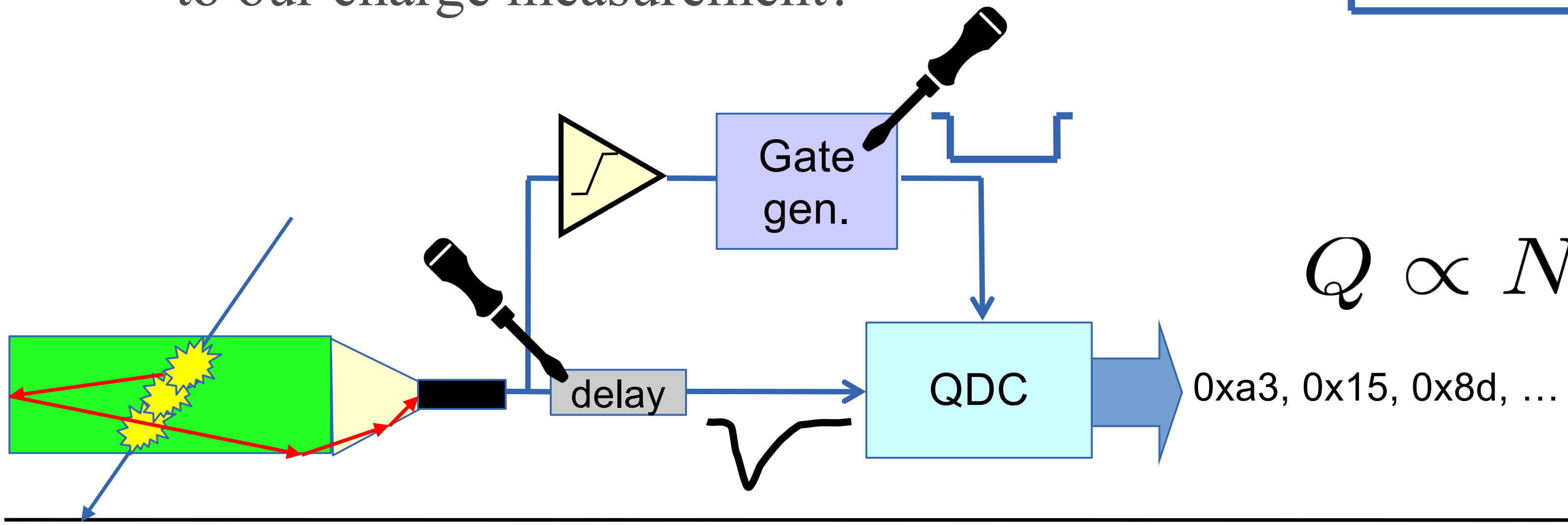
QDC: timing

- Relative timing between signal and gate is important
  - Delay tuning

Labs 2, 3, 4

- Gate should be **large enough** to contain the full pulse and to accommodate for the jitter
  - Fluctuations are always with us!
- Gate should **not** be **too large**
  - Increases the noise level
  - By the way, which is the noise contribution to our charge measurement?

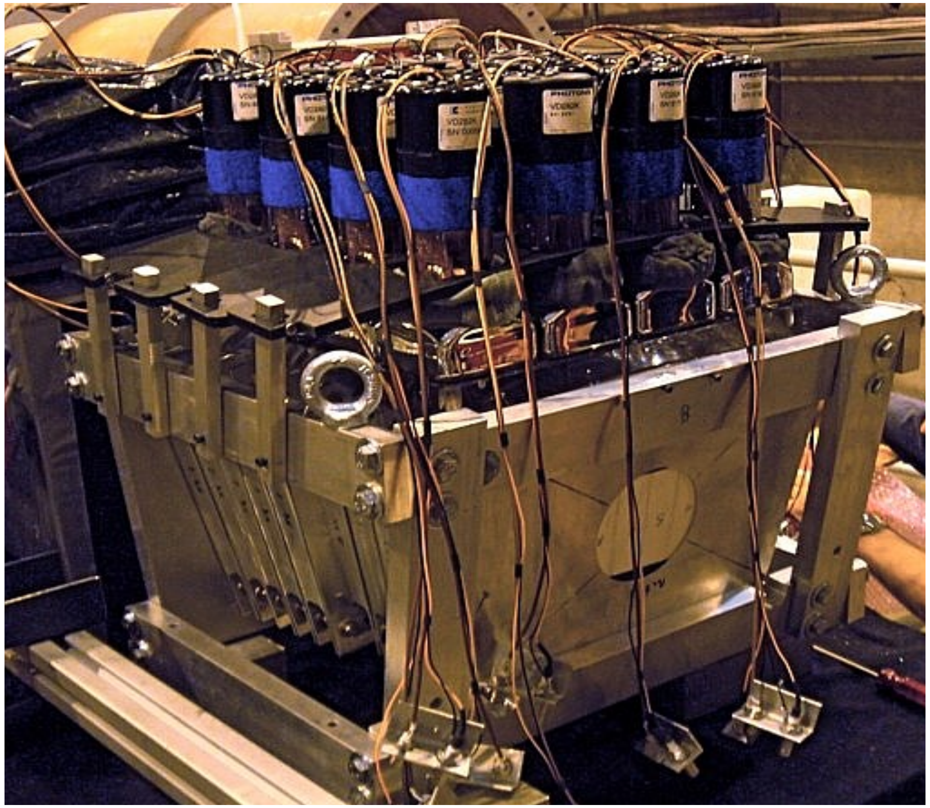


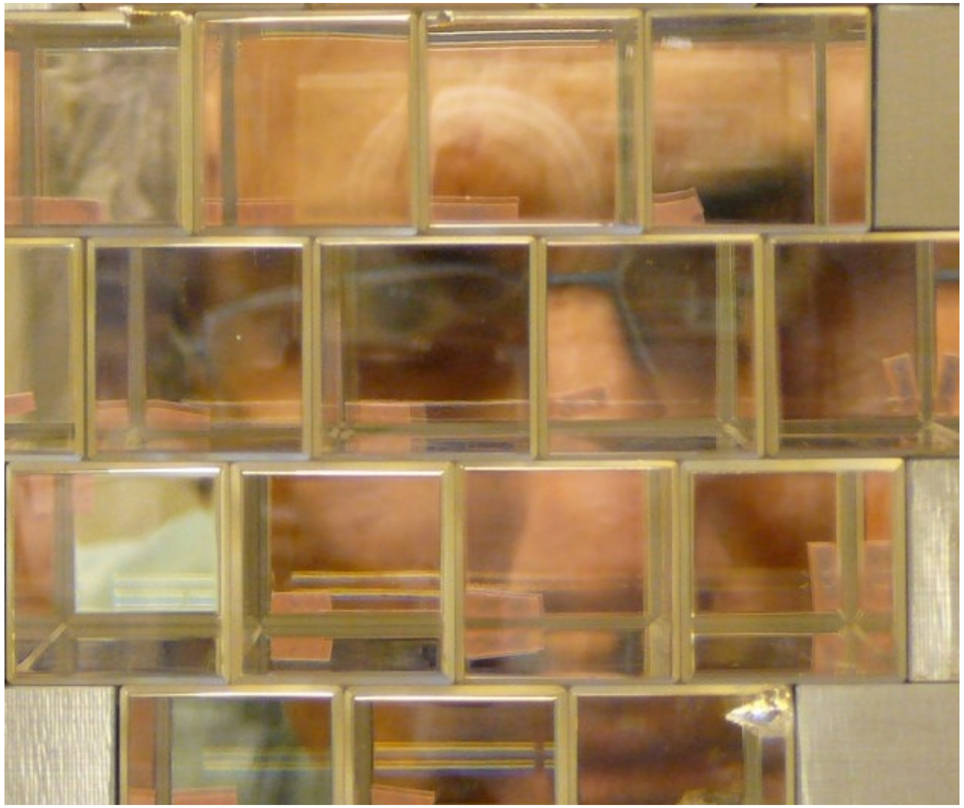


$$Q \propto N_\gamma \propto E$$

Example of QDC data

- Calorimetry R&D test beam @CERN
  - QDC spectra $Q \propto N_\gamma \propto E$



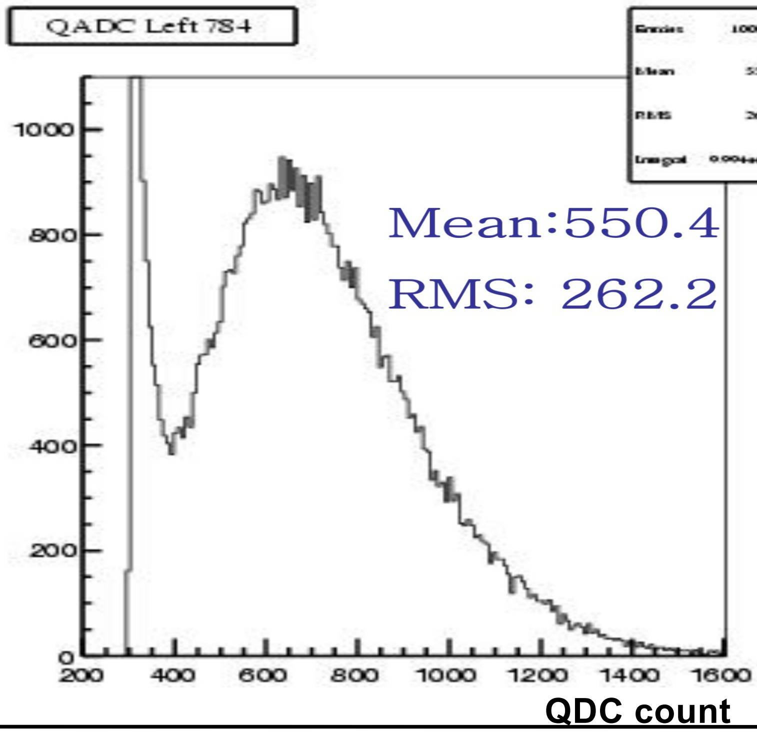


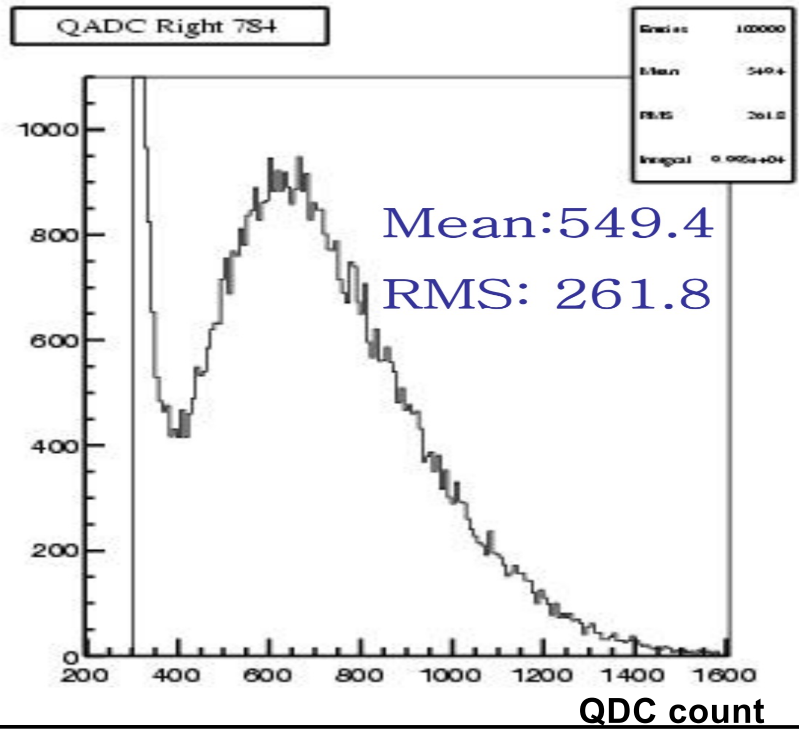
QDC spectra

- Calorimetry R&D test beam @CERN
  - QDC spectra

$$Q \propto N_\gamma \propto E$$

- But, what is the 1st peak?
  - How can we estimate it?





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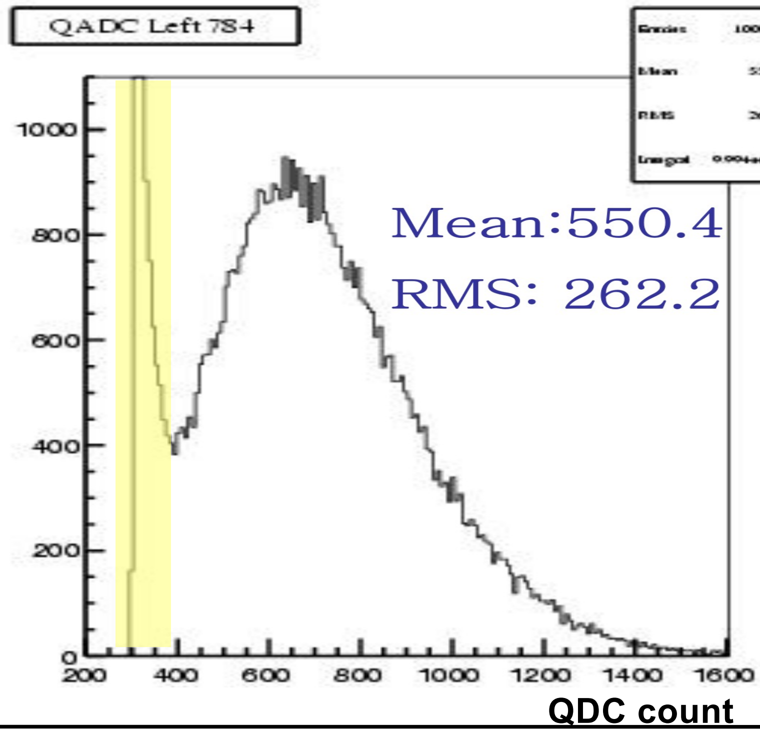
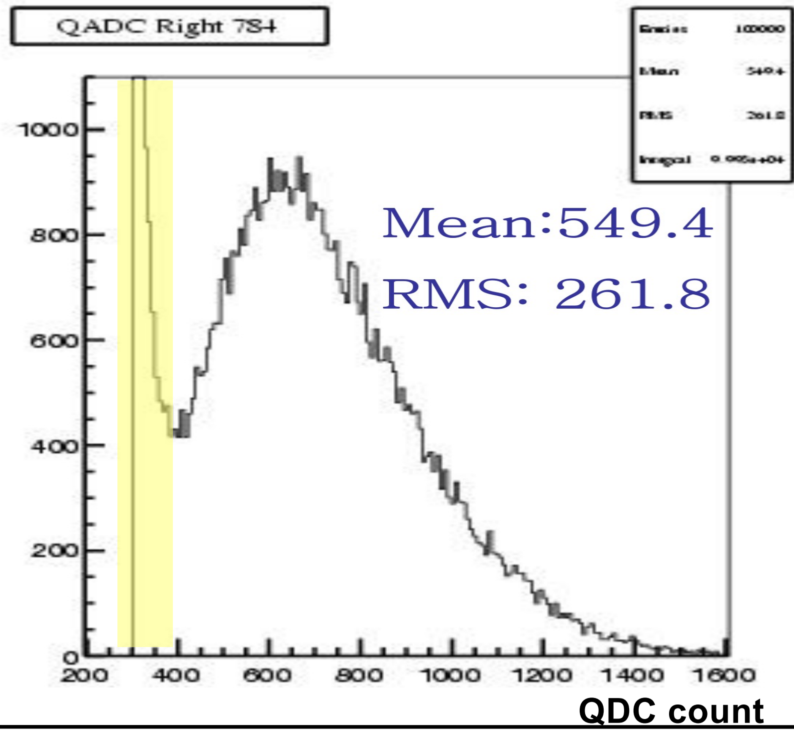
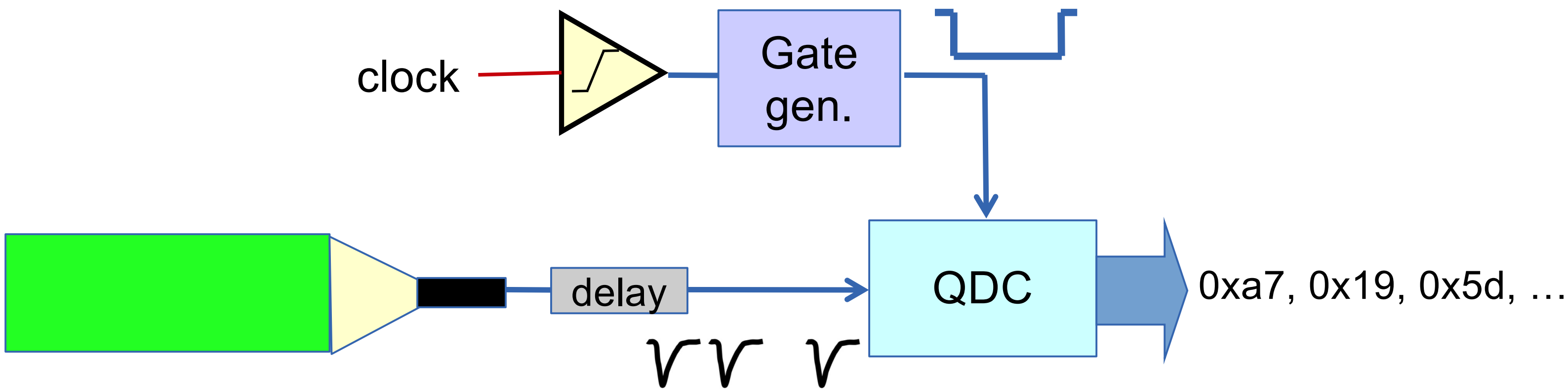




QDC: pedestal subtraction

- The pedestal can be measured with an out-of-phase trigger
  - PMT dark current, thermal noise, Jitter, fluctuations on power supply..
  - The same noise enters our physics measurements and contributes with an offset to the distribution
- The result of a pedestal measurement has to be subtracted from our charge measurements



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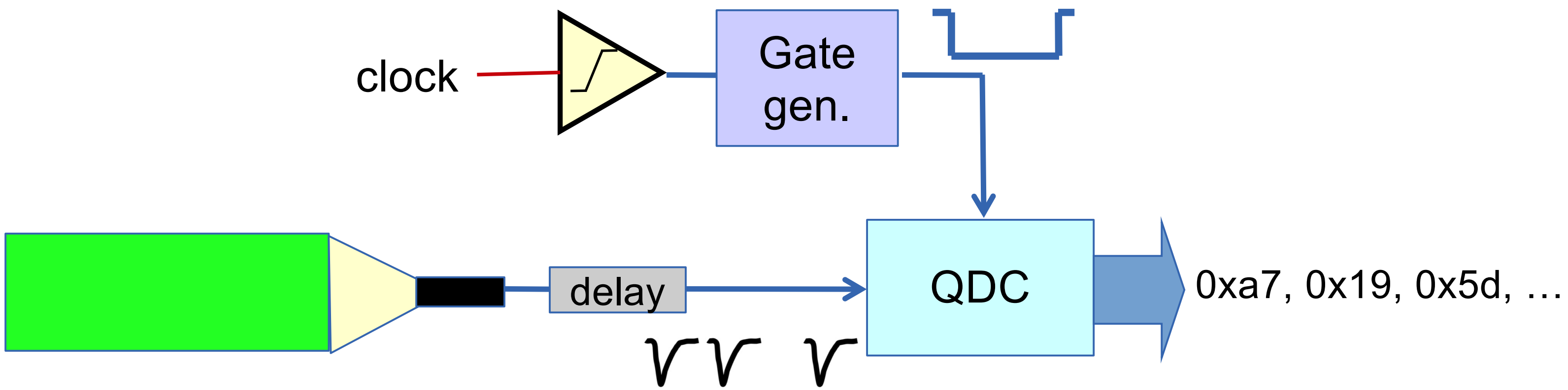
We essentially want to integrate the baseline of our setup



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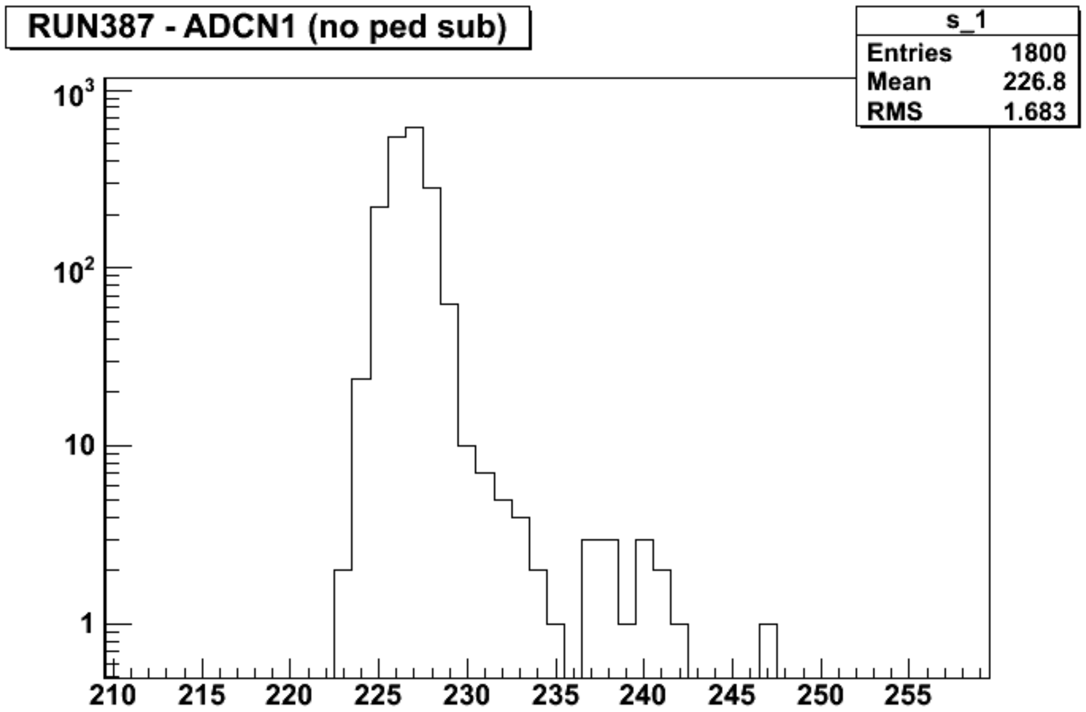
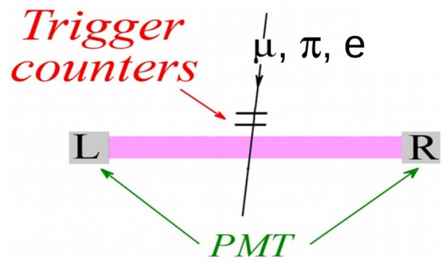
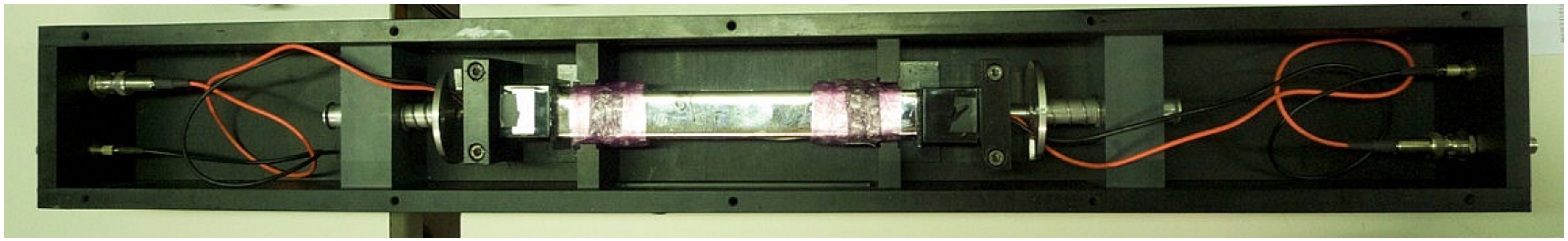


"Real" QDC at work

- $PbWO_4$ scintillating crystal equipped with two PMTs and exposed to e, μ and π beams
  - Real data from a test beam @CERN





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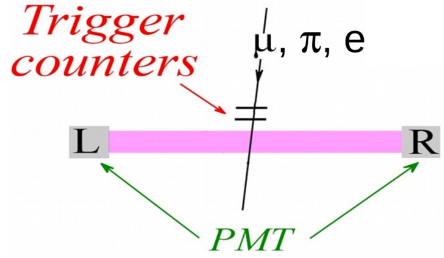
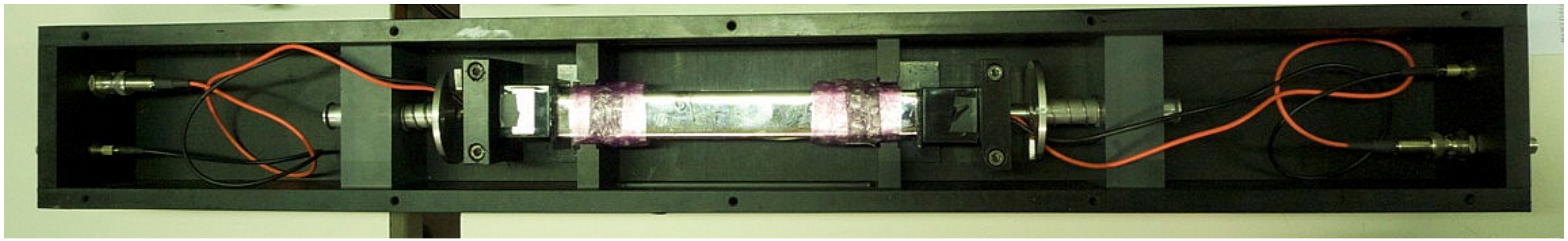


- A lot of effects will sum-up in a realistic case, like a test-beam
  - We can't feed our detector signal directly to the ADC (or QDC)
  - We have PMTs, transmission lines (with signal losses!), power supply fluctuations, impedance mismatches, reflections, distortions, etc..



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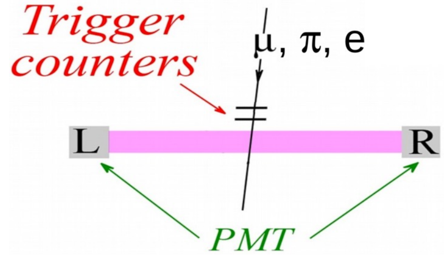
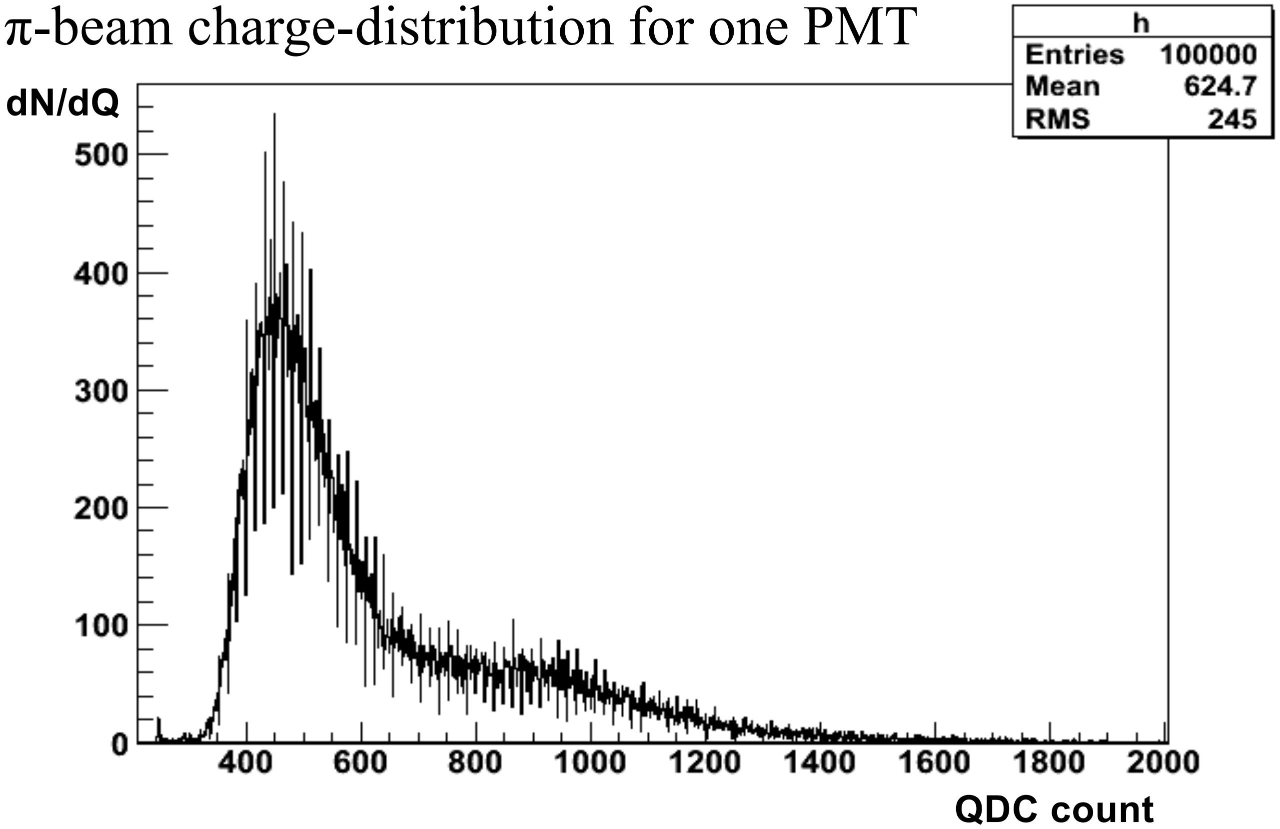


π-beam charge-distribution for one PMT



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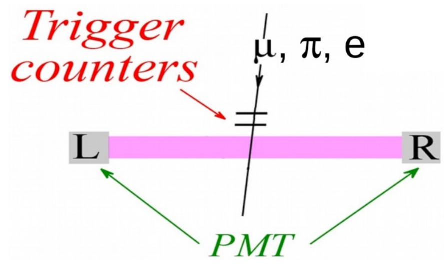

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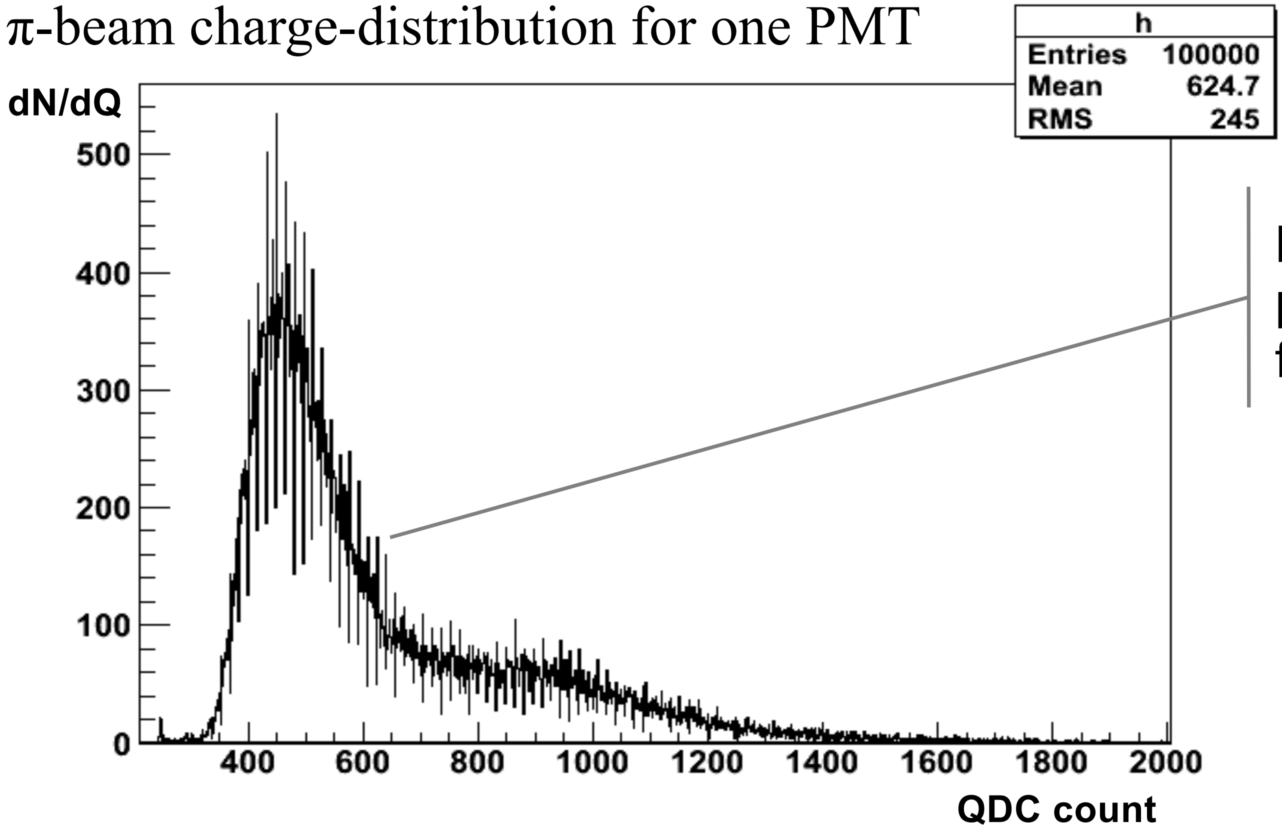

But, what are all those little peaks? Just statistical fluctuations?

Let's zoom in!

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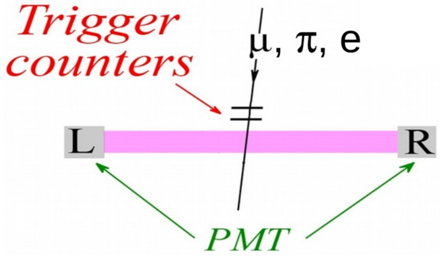

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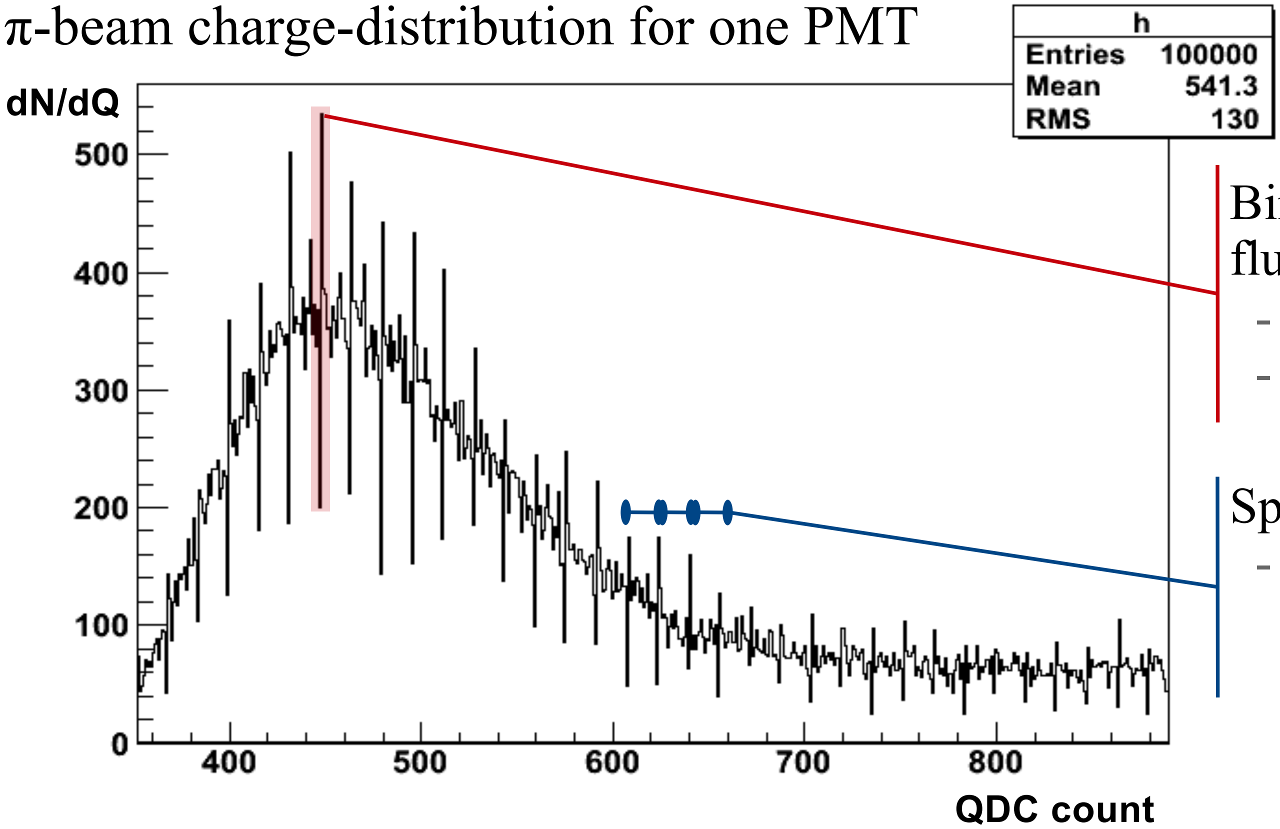

Bin with N entries can fluctuate with $\sigma = \sqrt{N}$
- expected $\sigma=\sqrt{360}\sim 19$
- observed ~200 (>10 σ)

Spikes are regularly distributed
- Some systematic effect must be taking place

Let's zoom in!

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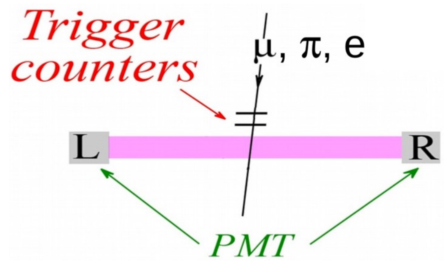

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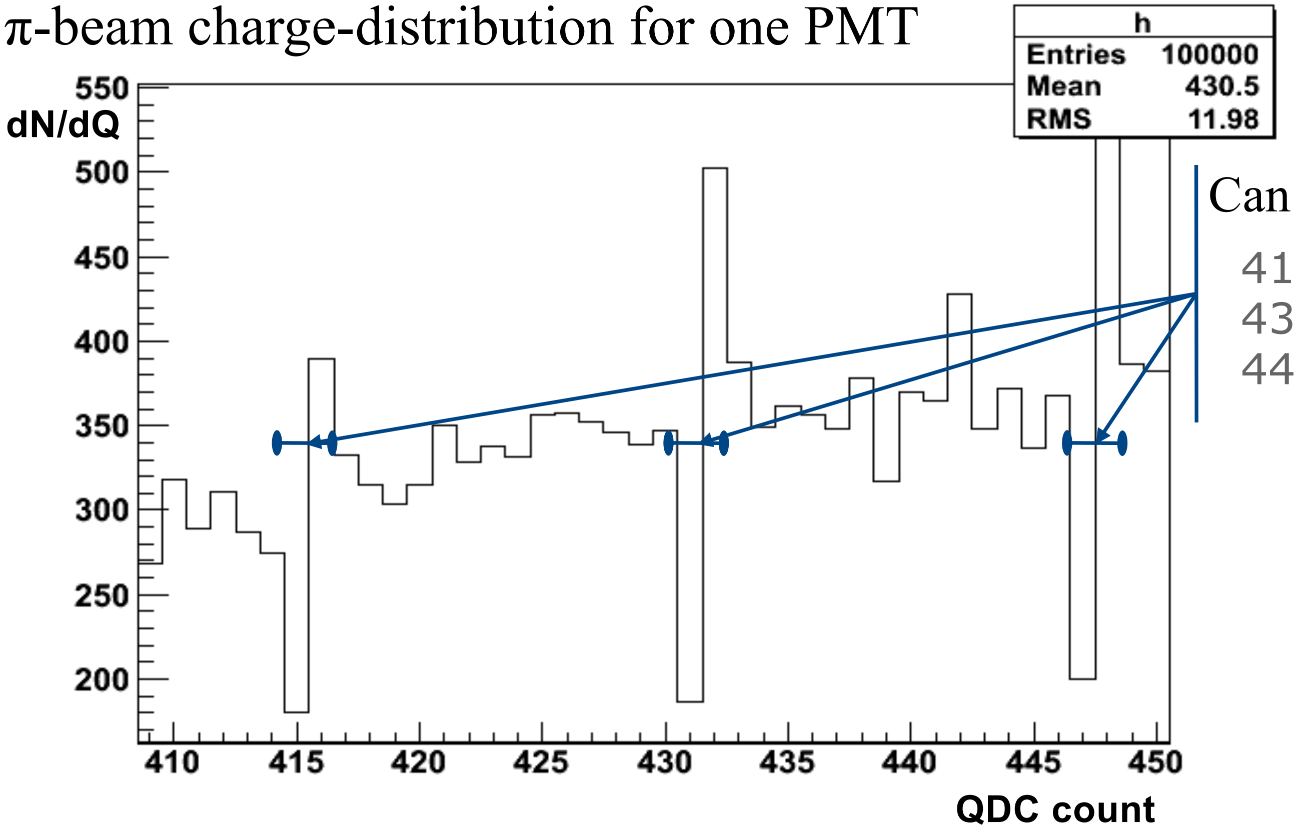

Can you see the effect?

415 & 416 –
431 & 432 –
447 & 448 –

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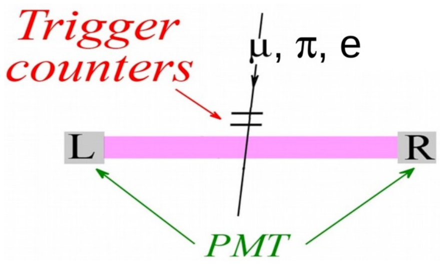

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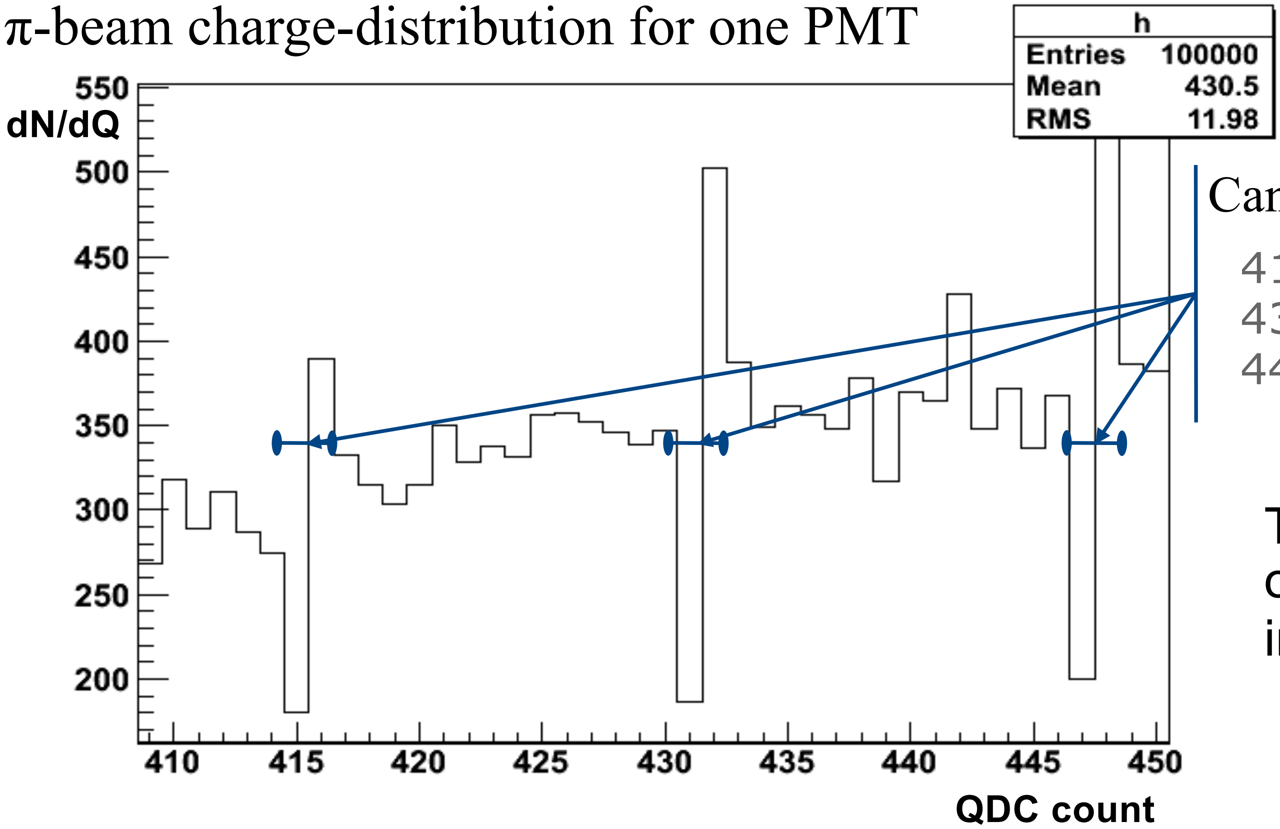


Can you see the effect?

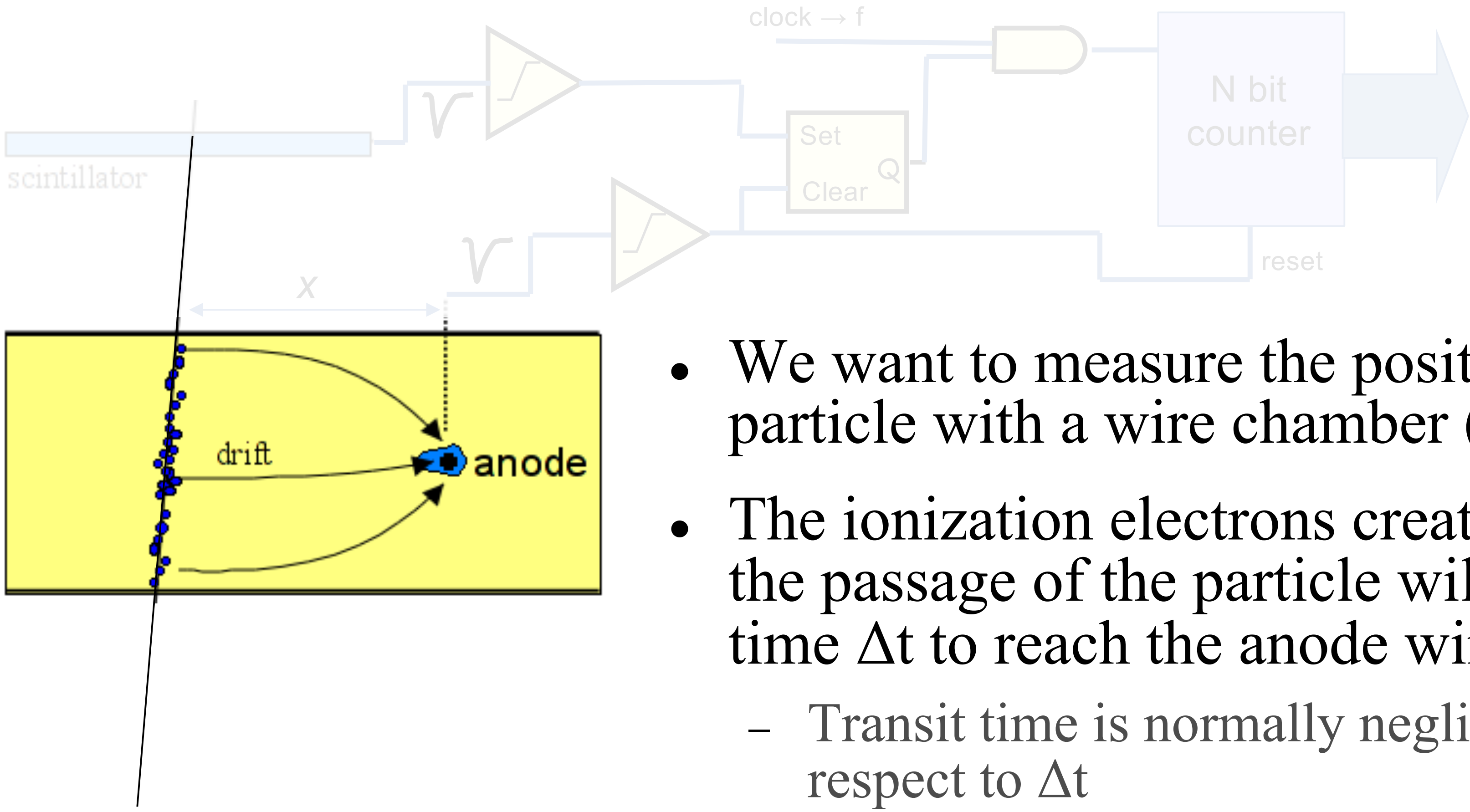
415 & 416 → 0x19**f** & 0x1A**0**
431 & 432 → 0x1A**f** & 0x1B**0**
447 & 448 → 0x1B**f** & 0x1C**0**

The QDC prefers output of type `0x...0` in respect of `0x...f`

Outline

- Introduction
  - DAQ, Electronics & Readout Chain
- Measure energy deposition
  - Scintillator setup
  - Photomultiplier
  - Analog-to-Digital conversion
  - Charge-to-Digital conversion
  - QDC in real life
- Measure position
  - Wire chamber setup
  - Time-to-Digital conversion
  - TDC in real life
- Corollary

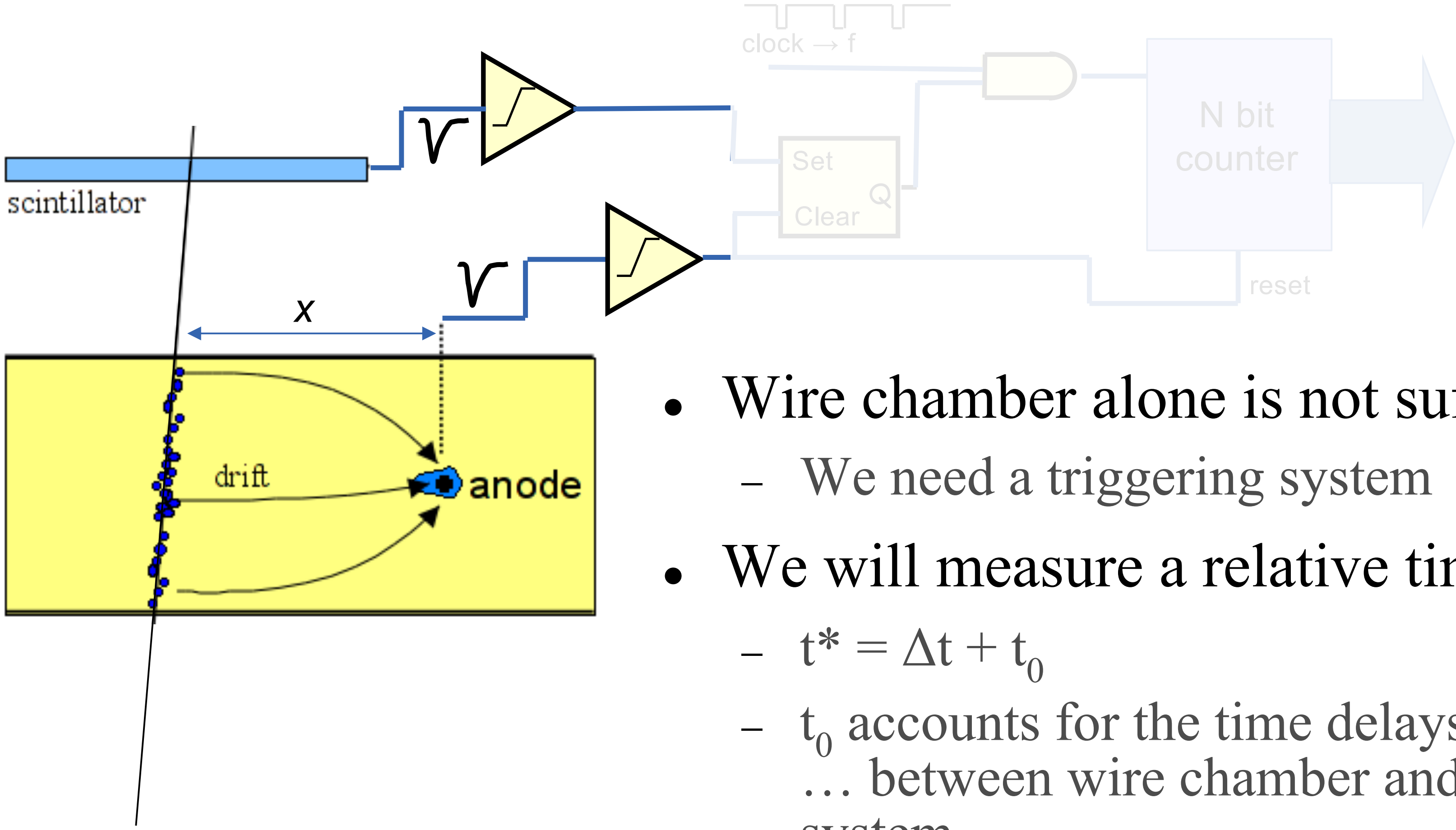
Position measurement



- We want to measure the position of particle with a wire chamber (**drift**)
- The ionization electrons created by the passage of the particle will take a time Δt to reach the anode wire
  - Transit time is normally negligible with respect to Δt
  - If we consider a constant drift speed v_D (e.g.: 50 μm/ns), then position is:

$$\mathbf{x = v_D \cdot \Delta t}$$

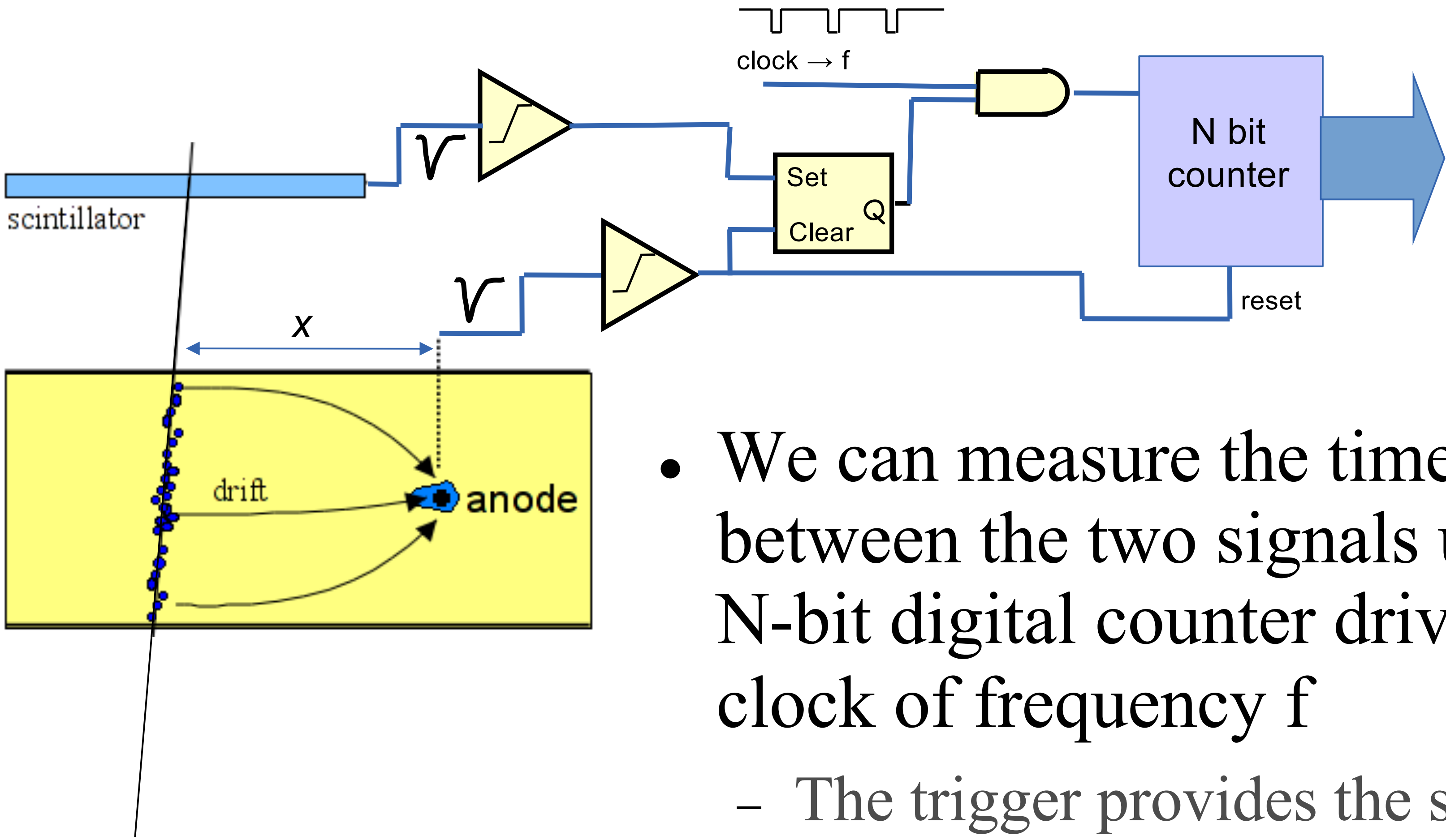
Triggering



- Wire chamber alone is not sufficient
  - We need a triggering system
- We will measure a relative time
  - $t^* = \Delta t + t_0$
  - t_0 accounts for the time delays, offsets, … between wire chamber and triggering system
- Assuming a constant drift

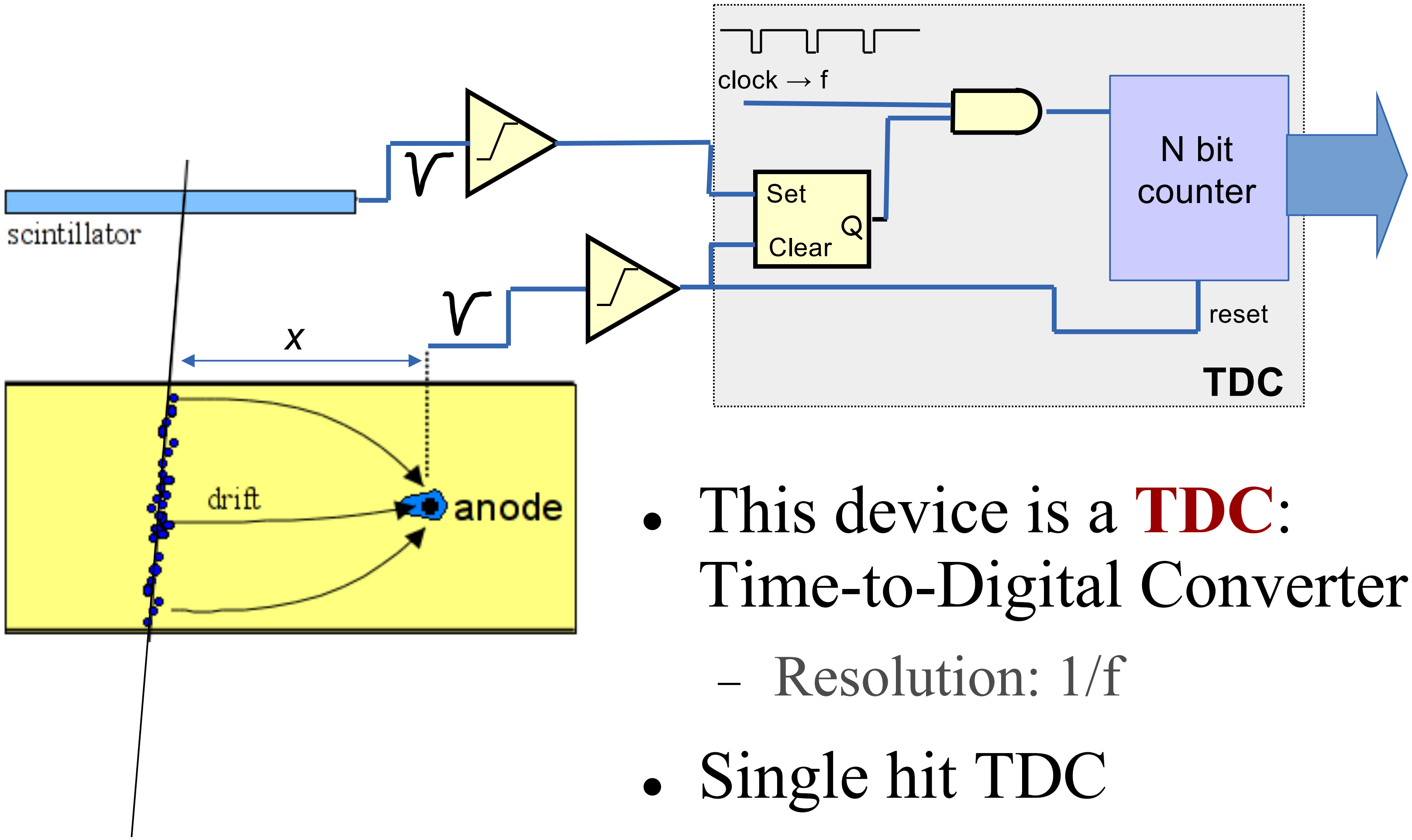
$$x = \alpha t^* + \beta$$

Time measurement



- We can measure the time offset between the two signals using a N-bit digital counter driven by a clock of frequency f
  - The trigger provides the start signal
  - Wire signal acts as a stop signal

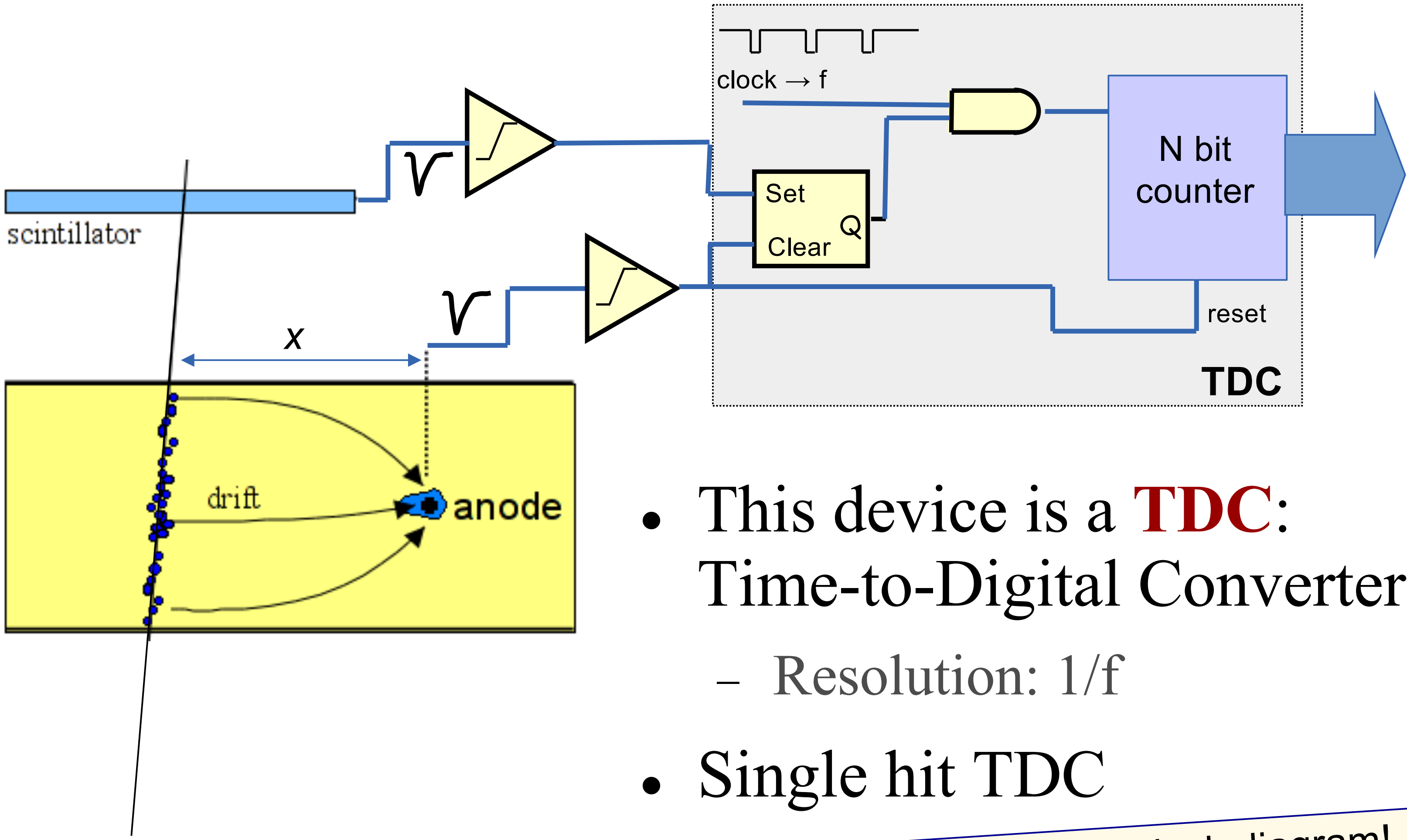
Time measurement: TDC

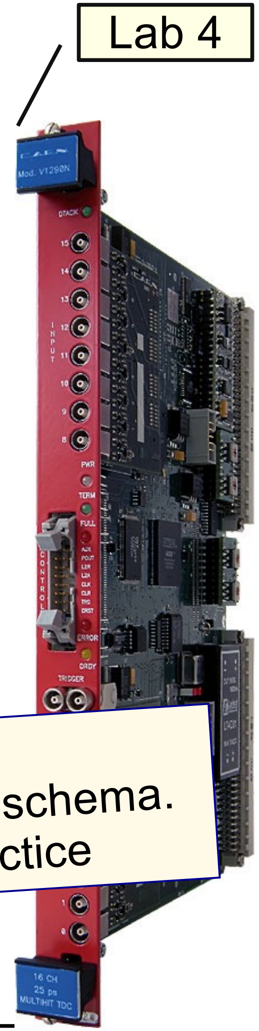


- This device is a **TDC**: Time-to-Digital Converter
  - Resolution: 1/f
- Single hit TDC
  - if a noise spike comes just before the wire signal, the measure is lost

Lab 4

Time measurement: TDC





- This device is a **TDC**: Time-to-Digital Converter
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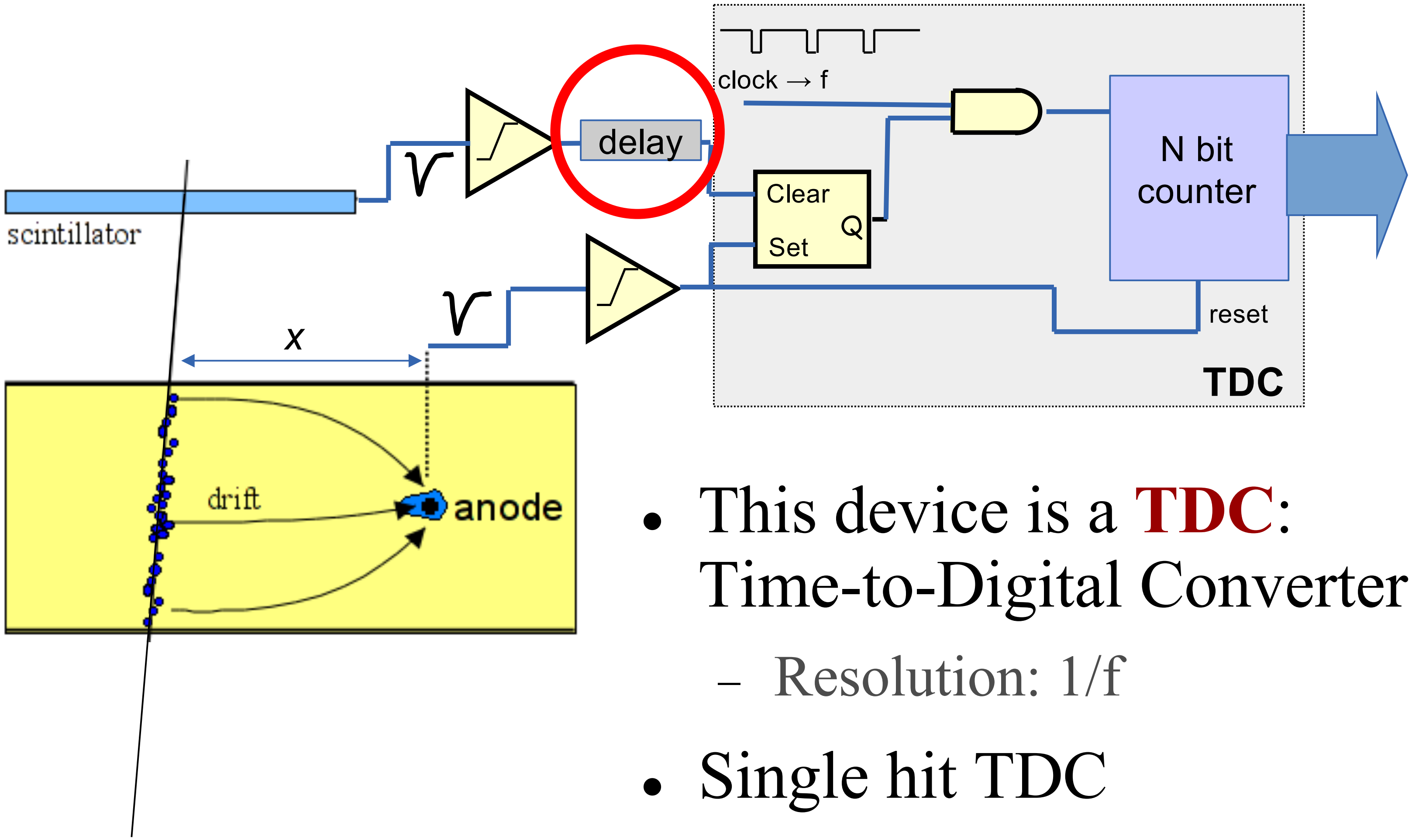
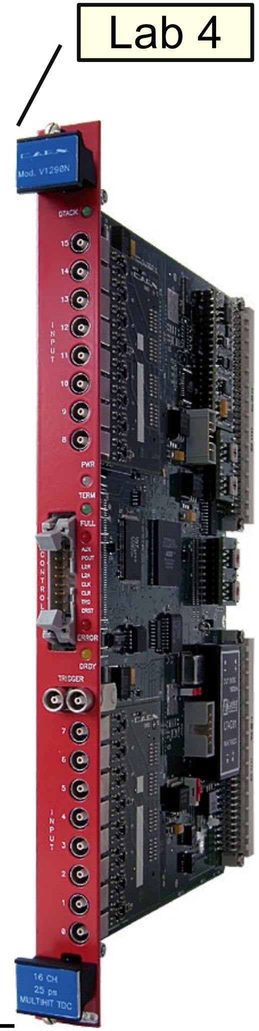
Very simplified block diagram!
Many complicated parts not present on the schema.
Clock gating is NOT a good design practice

Time measurement: TDC





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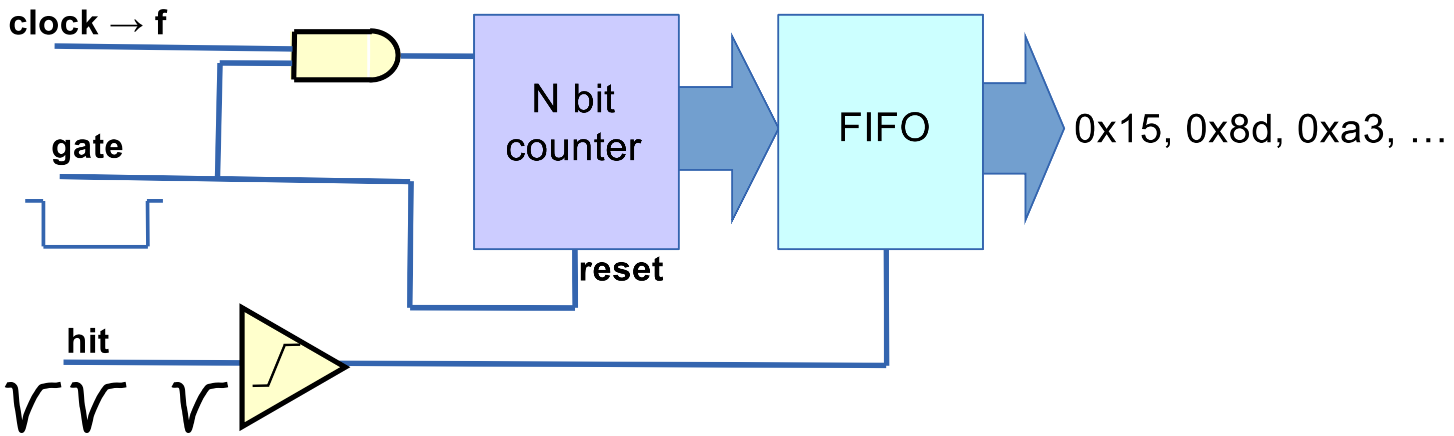
Multi-hit TDC

- Gate resets and starts the counter
  - It also provides the measurement period
- Each "hit" (i.e. signal) forces the FIFO to load the current value of the counter, that is the delay after the gate start
  - Common-start configuration
  - In order to distinguish between hits belonging to different gates, some additional logic is need to tag the data



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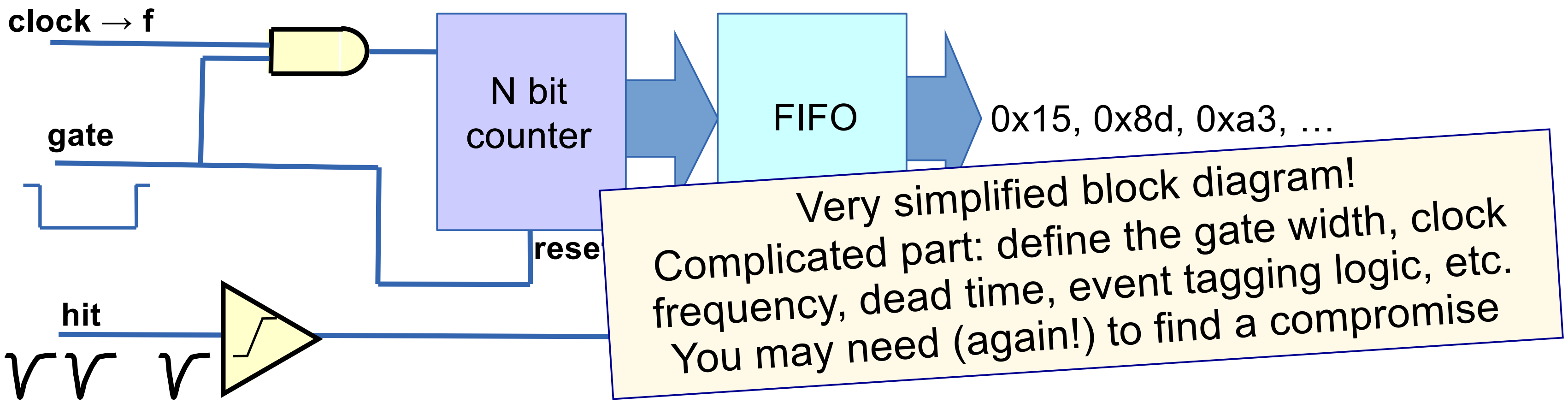
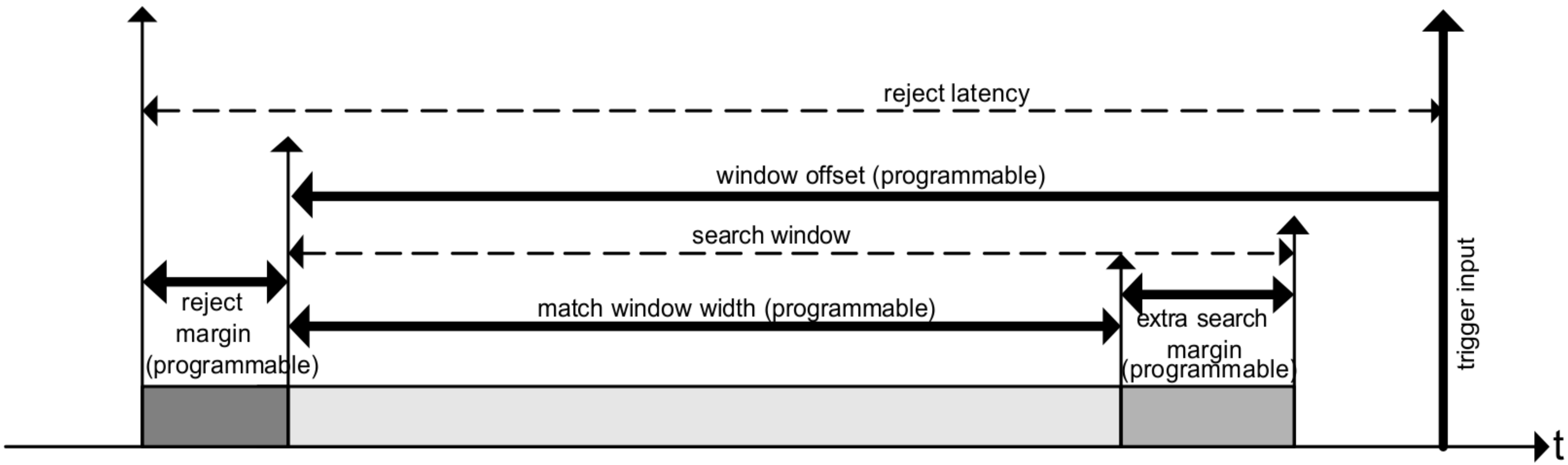


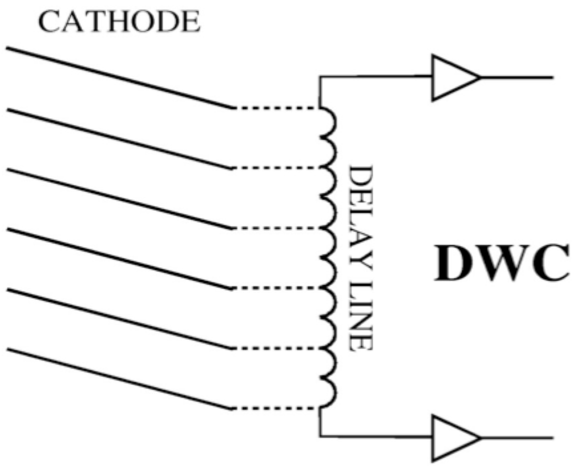
Actual TDCs

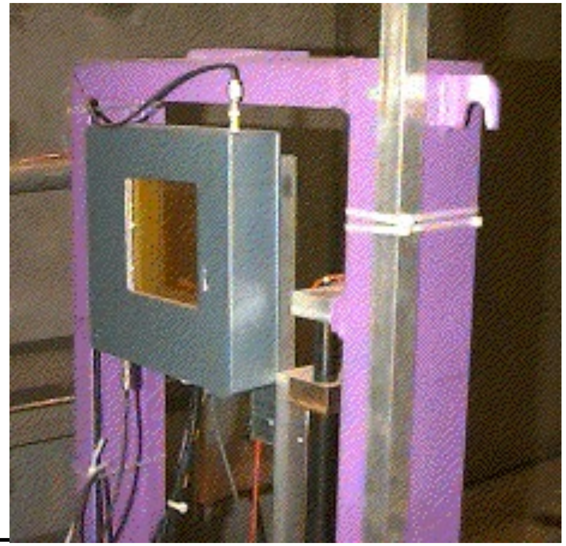
- Plenty of TDCs architectures available on the market
  - Common Start, Common Stop, Charging Capacitor, Vernier, etc.
- Real TDCs provide advanced functionalities for fine-tuning the hit-trigger matching
  - Internal programmable delays or generation of programmable gates
  - Programmable rejection frames
  - Usually via a dedicated C library/API



Real life wire chamber & TDC

- XDWC: delay wire chambers
  - used on the SPS extracted lines to measure beam profiles
- Two cathode planes provide X and Y positions
  - Measurement based on the delay gained along a delay line





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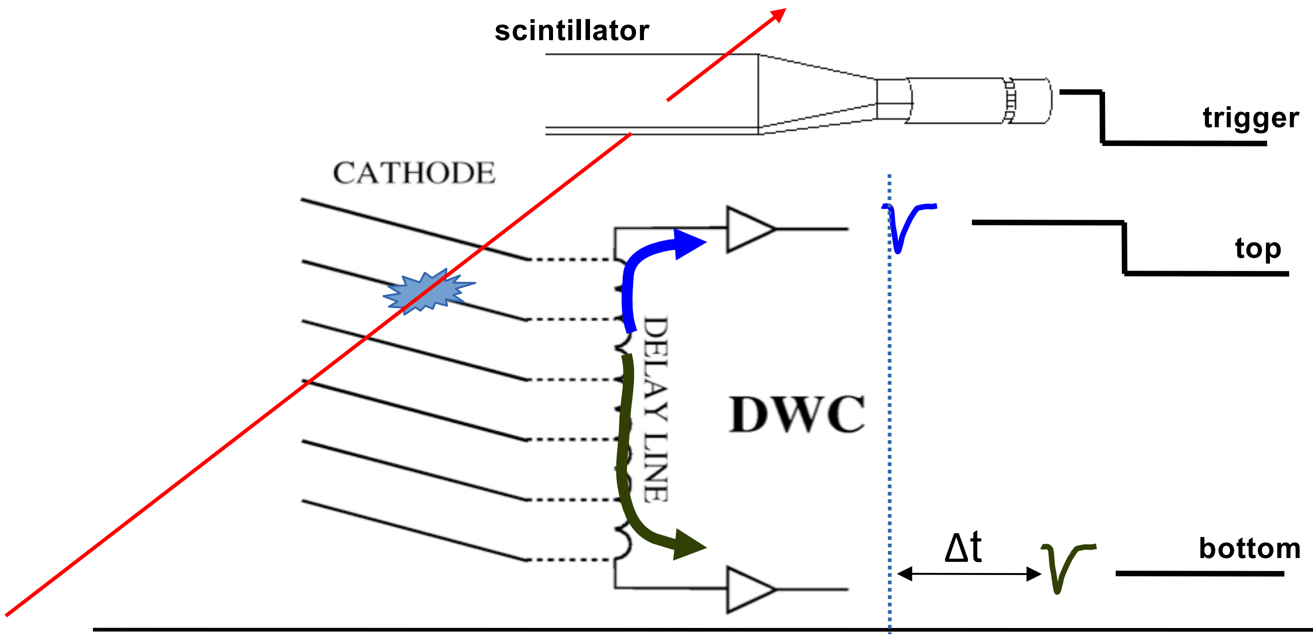
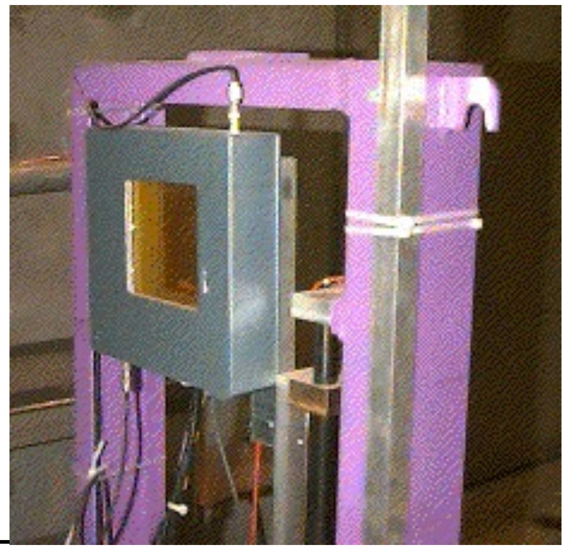
$$y = \alpha \cdot \Delta t + \beta = \alpha \cdot (t_{top} - t_{bottom}) + \beta$$





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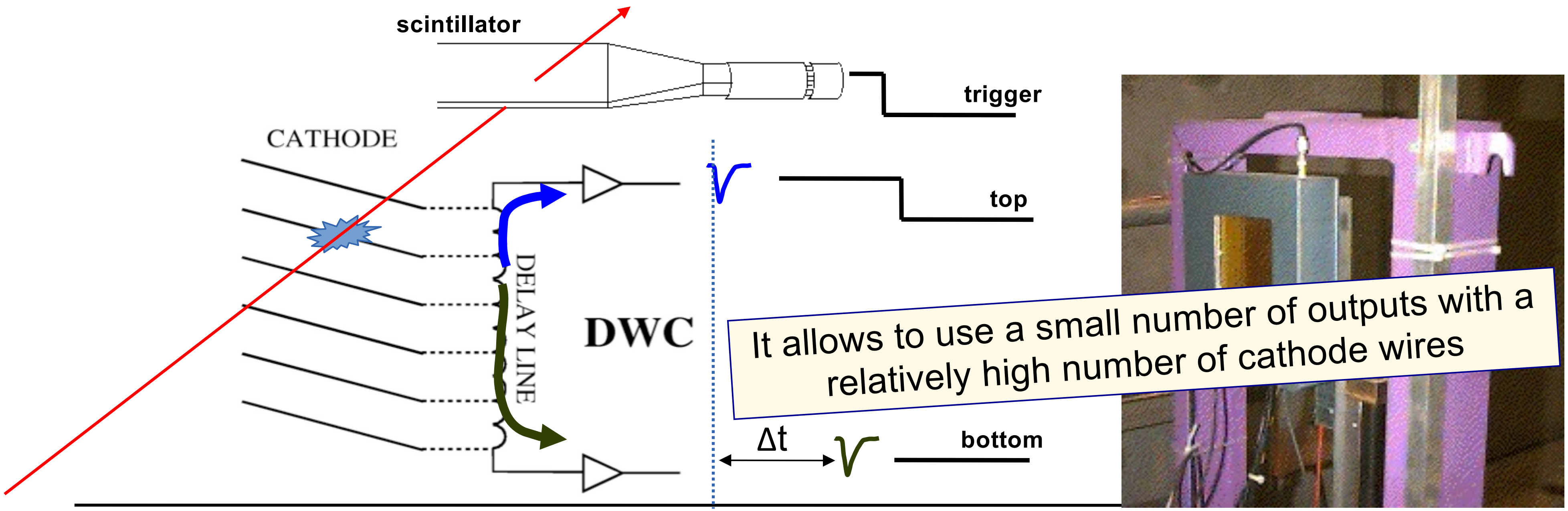
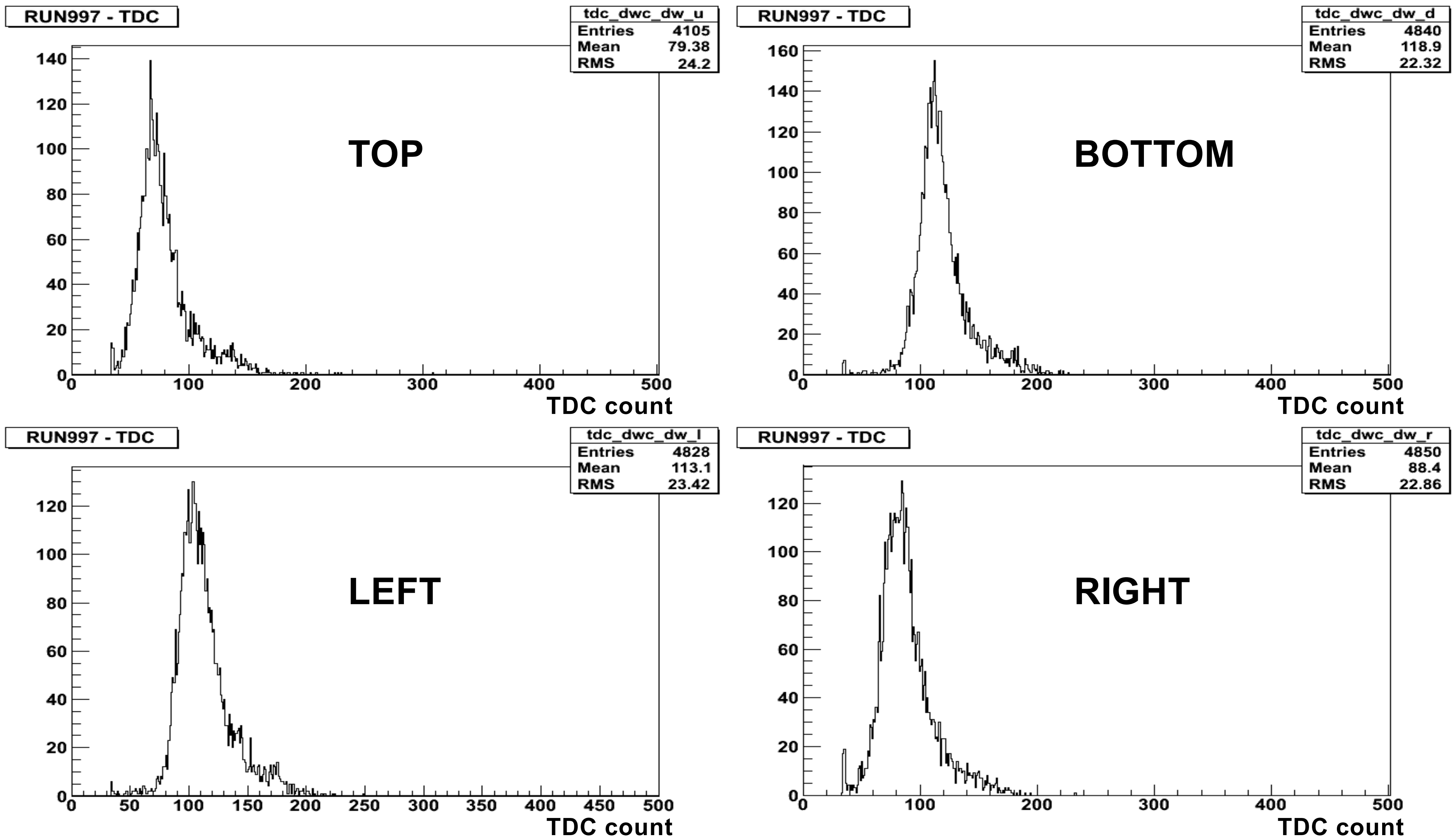


It allows to use a small number of outputs with a relatively high number of cathode wires

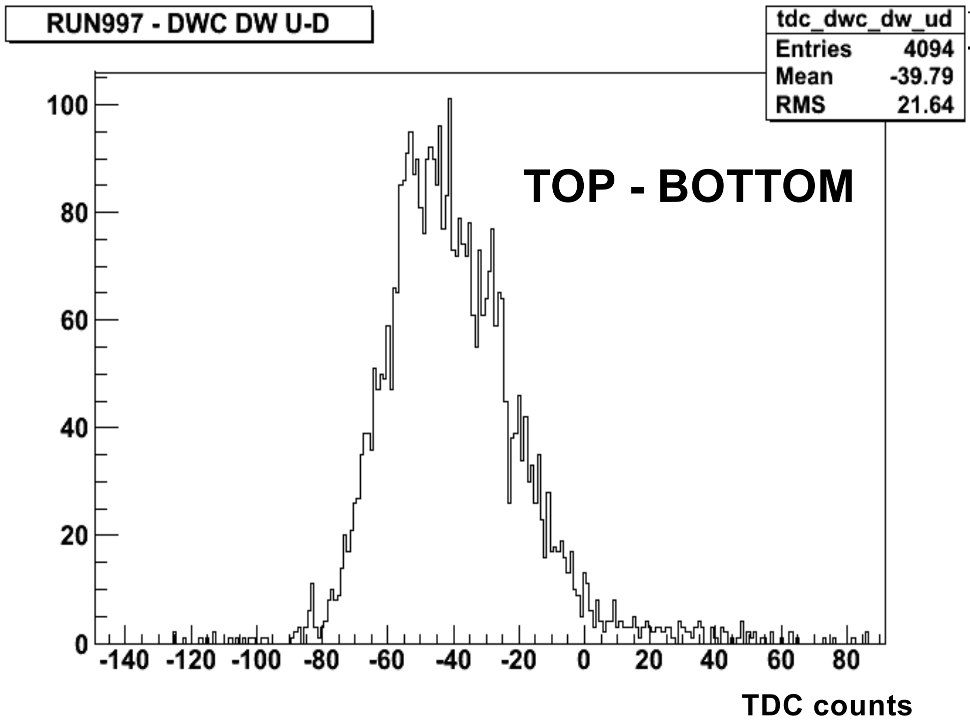
Raw time data

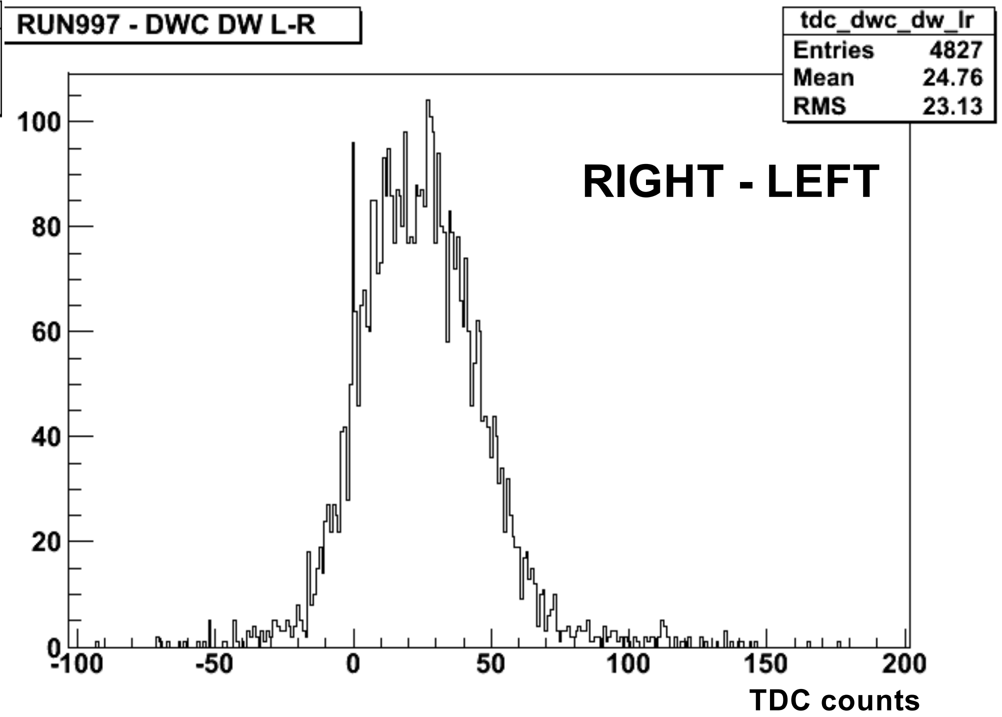
- Take a run (some thousands events)
  - Individual channel distribution



Un-calibrated beam profile

- Beam sizes are still in TDC counts
  - Not very useful, though
  - How do we convert this into a known scale (e.g. cm)?





Outline

- Introduction
  - DAQ, Electronics & Readout Chain
- Measure energy deposition
  - Scintillator setup
  - Photomultiplier
  - Analog-to-Digital conversion
  - Charge-to-Digital conversion
  - QDC in real life
- Measure position
  - Wire chamber setup
  - Time-to-Digital conversion
  - TDC in real life
- Corollary: calibration

Calibration

- Previous experiments provide relative measurements
  - Values obtained via our systems are in some (known) relation with the interesting quantities
    - Scintillator $Q \propto N_\gamma \propto E$
    - XDWC $y = \alpha \cdot \Delta t + \beta = \alpha \cdot (t_{top} - t_{bottom}) + \beta$
- Our instruments need to be calibrated in order to give us the answer we are looking for
  - We have to determine the **parameters** that transform the raw data into a physics quantity
  - The parameters normally depend on the experimental setup (e.g. cable length, delay settings, HV settings, …)
  - Sometimes these parameters might depend on the detector itself (e.g. ageing of a scintillator may influence efficiency, light yield,...)

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However, we still don't know the proportionality factor between charge and energy, or between time and position

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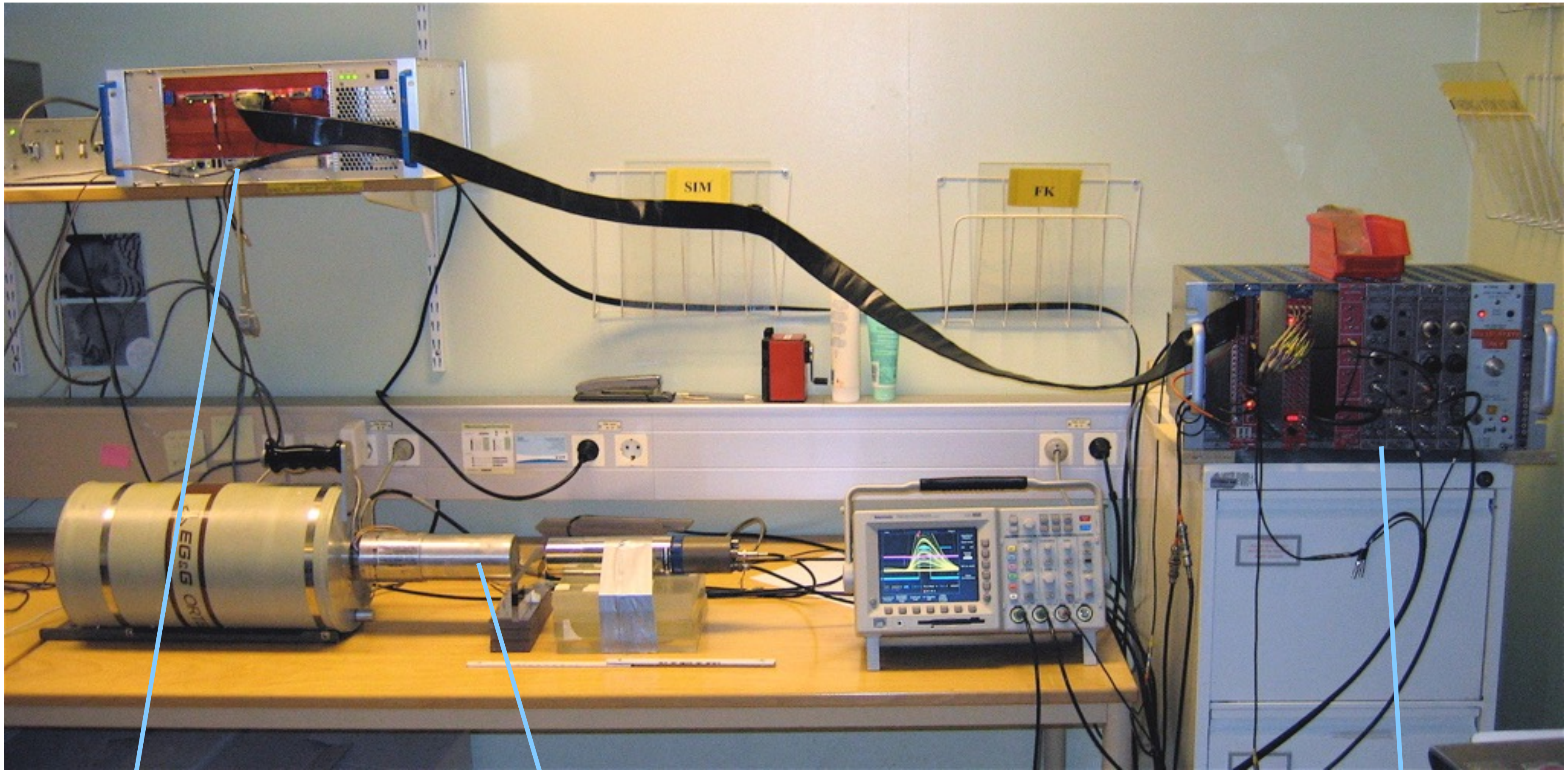
N.B.: calibration mechanisms/procedures shall be always foreseen in the design of our detector and DAQ

E.g.: Ge Crystal for isotope ID



Trigger and front-end

Crystal HPGe
Radiation detector

Readout (ADC)

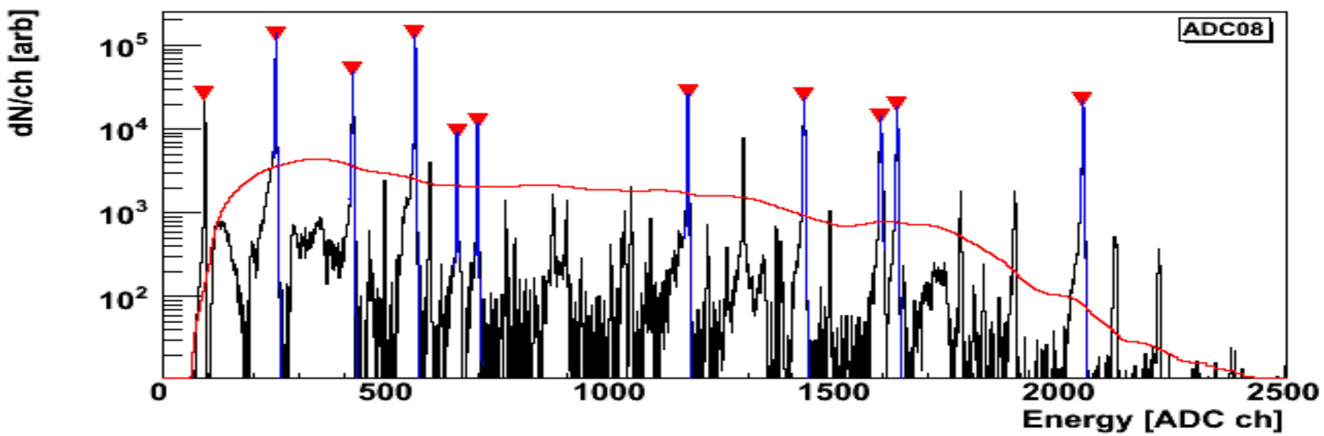
by Sergio Ballestrero

Ge crystal calibration

- ^{152}Eu reference source allows for definition of the parameters describing functional relation between ADC count and E
  - Known γ emission lines

$$Q \propto N_\gamma \propto E$$

- Find the peaks and fit



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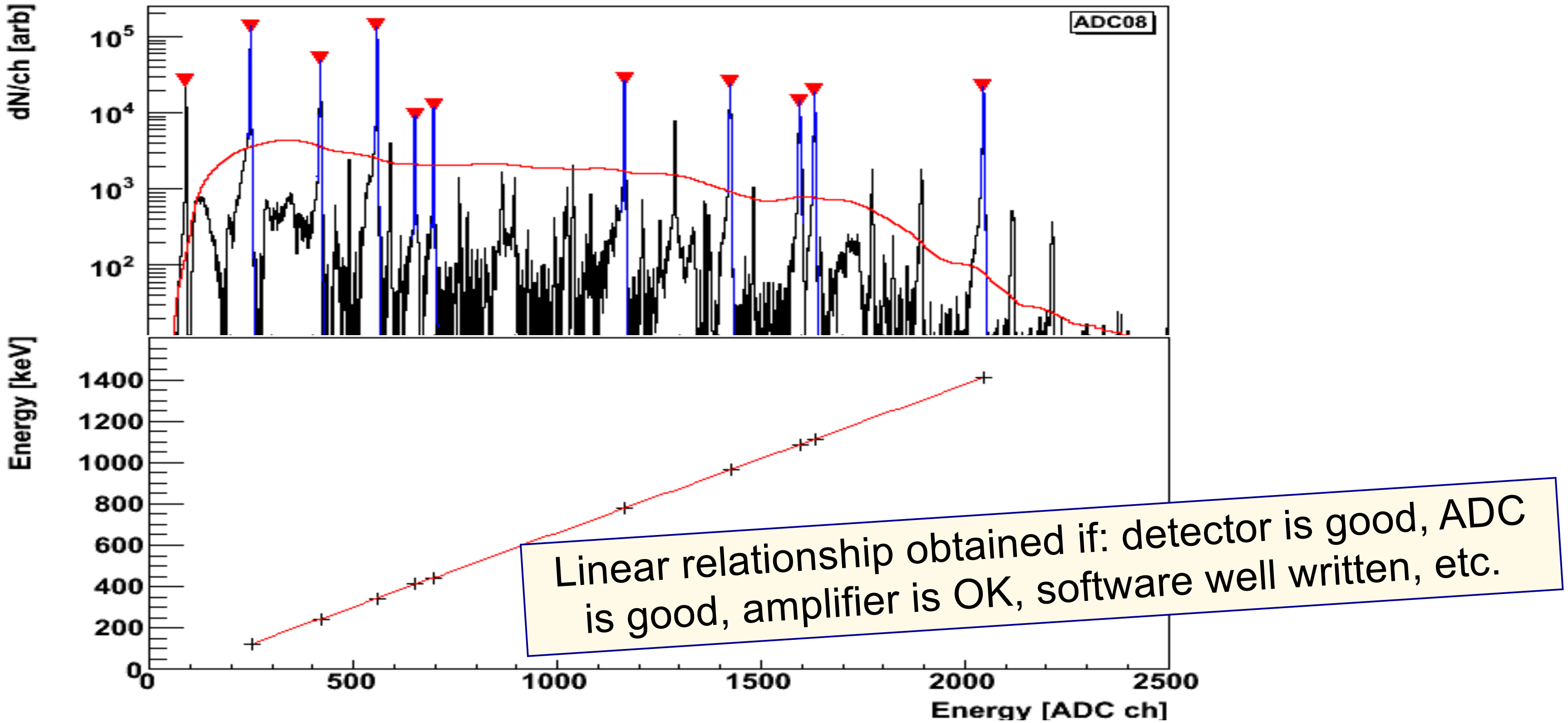
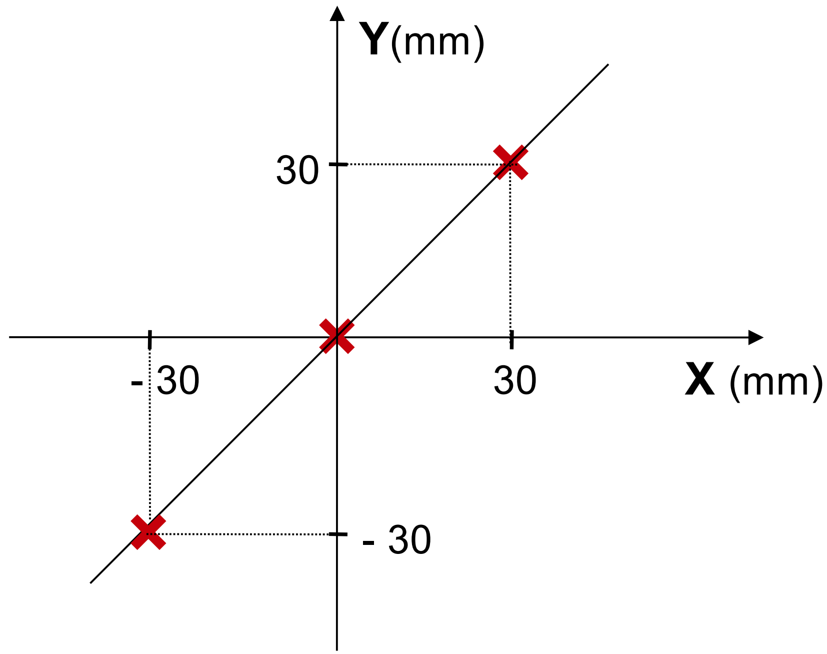


Back to XDWC: calibration

- XDWC chamber have 3 calibration inputs
  - allow for independent calibrations of X and Y axes with only 3 different sets of data
  - Calibration input simulate signals from particles respectively hitting
    - Right-top (X=Y=30mm)
    - Center (X=Y=0mm)
    - Left-bottom (X=Y=-30mm)
  - Interpolating the three points in t-x space, the parameters of the calibration equation can be measured



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- Calibration shall be done with final setup and TDC

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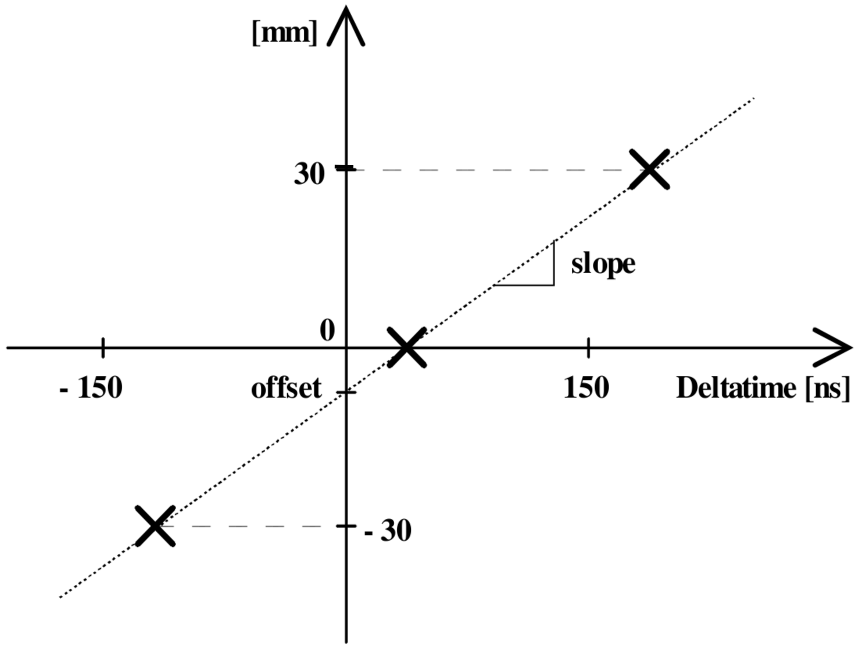

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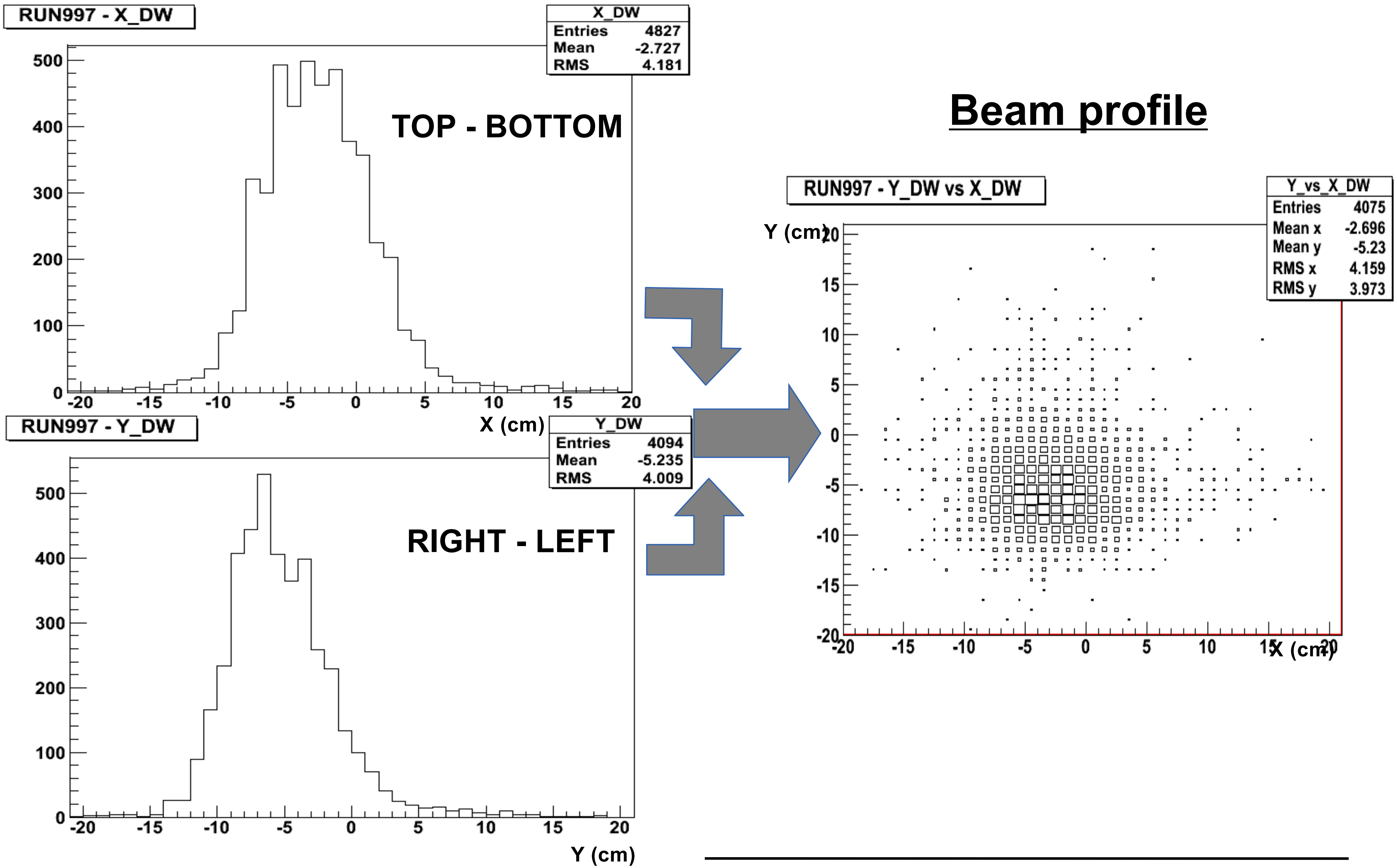
Calibrated XDWC



Wrap-up

- Digitization techniques produce data directly manageable by digital systems (e.g. a computer)
  - Greatly simplifies the down-stream data-handling
  - Available on a variety of platforms: VME, ATCA, PCI, USB, …
  - Root of every modern DAQ system
- Frequently you have to open the "black box" and see where numbers come from
  - Real electronics does not behave as the ideal one

- Trade-offs between speed/precision/cost exist
  - You have to choose the solution that best suits you
- Physics quantities are derived from raw data via calibration
  - Calibration procedures to be foreseen for your detector/DAQ

Thank you!